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Spectral control methods and applications for multi-channel LED light engines

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Abstract

Lighting installations are usually static and based on long-standing visual indicators such as colour temperature, colour rendering, and illuminance values. However, we now know that spectral variations in light elicit non-visual effects via a distinct pathway in our brain, and it is important for designers and architects to take these into account: light influences our mood, modulates our attention, can suppress the production of melatonin and can shift our circadian rhythms. Considering all the spectral aspects of light is the initial step towards designing healthier environments that are both pleasant and respectful to our biology. Multi-channel LED light engines can provide the core technology for a truly spectral lighting design, thereby enabling wider applications of light with different purposes.

This dissertation aims at facilitating this transition by delivering cost-effective multi-channel LED light engines capable of generating arbitrary spectral shapes. In the first part of this work, we develop a light engine for a research-oriented market and explore novel designs and solutions for an advanced industrial device aimed at tackling a more general lighting market. These two efforts led to the development of two optically and spectrally different devices: the SPECTRA TUNE LAB light engine (with an on-board spectrometer and ten different LED channels), and the VEGA 07 light engine (equipped with a colour sensor and seven different LED channels).

Second, to generate arbitrary spectral shapes, we perform an extensive study on different heuristic algorithms implemented directly in the microcontroller of the light engine as well as in its control software. We show that the simulated annealing algorithm provides fast computation times with excellent spectral fidelity.

Third, we develop two types of optical feedback controllers with different light sensors to prevent temperature-driven colour and spectral shifts, and the wear-out of the LEDs. Both these sensors, i.e. the spectrometer in the SPECTRA TUNE LAB and the colour sensor in the VEGA 07, are used to ensure high precision and accuracy of the emitted light at all times and for any kind of target spectrum.

Finally, we demonstrate the ways in which these devices can be used for different applications, thereby verifying the huge advantages and added value of this technology as compared to traditional lighting systems. Our developed light engines were installed in the intensive care units of two hospitals (Hospital Vall d'Hebron

and Hospital Clínic in Barcelona), in office settings (ARUP's office in London), and 24/7 control rooms (Repsol's refinery control room in Tarragona), among others.

Resum

Les instal·lacions d'il·luminació solen ser estàtiques i basades en indicadors visuals clàssics com la temperatura de color, la representació dels colors o els nivells d'il·luminació. Tanmateix, avui sabem que la llum també té una funció que no és propiament visual i que els arquitectes i dissenyadors haurien de començar a tenir en compte: la llum pot influir en el nostre estat d'ànim, modular la nostra atenció, regular la producció de melatonina o modificar els ritmes circadiaris. Tenir en compte totes les propietats espectrals de la llum és el primer pas per dissenyar entorns més sans i respectuosos amb la nostra biologia. Així, el disseny i desenvolupament de noves fonts de llum LED multicanal assequibles serà la tecnologia que permetrà un autentic canvi de paradigma espectral i començar a utilitzar la llum per a múltiples aplicacions.

Aquest treball té com a objectiu facilitar aquesta transició proporcionant fonts de llum LED amb capacitat per generar qualsevol tipus de forma espectral. En una primera part, hem desenvolupat un sistema d'il·luminació multicanal orientat a un mercat d'investigació i recerca, i hem explorat nous dissenys i solucions per a un dispositiu més industrial amb l'objectiu de penetrar al mercat d'il·luminació general. Els dos esforços s'han materialitzat en dos dispositius òpticament i espectralment diferents: el sistema de llum SPECTRA TUNE LAB (amb un espectròmetre a l'interior i 10 canals LED diferents) i el sistema de llum VEGA 07 (amb un colorímetre i 7 canals LED diferents).

En segon lloc, per poder crear qualsevol tipus de forma espectral, hem estudiat diferents algorismes heurístics implementats directament al micro-controlador de la lluminària o en un programari extern. L'algorisme desenvolupat de *simulated annealing* ha resultat ser el més ràpid amb una fidelitat espectral excel·lent.

En tercer lloc, hem desenvolupat dos tipus de controladors òptics de llaç tancat amb dos sensors de llum diferents per evitar canvis de color i canvis espectrals degut a increments de la temperatura o degradació dels LEDs. Ambdós sensors, l'espectròmetre per l'SPECTRA TUNE LAB i el colorímetre pel VEGA 07, s'utilitzen per assegurar que la llum emesa romangui precisa i estable en tot moment, per a qualsevol espectre que vulguem generar.

Finalment, demostrem com aquests dispositius es poden utilitzar per a diferents aplicacions oferint grans avantatges en comparació amb sistemes tradicionals. El

nostre sistema d'il·luminació s'ha instal·lat a la unitat de cures intensives d'hospitals (a l'Hospital Vall d'Hebron i a l'Hospital Clínic, a Barcelona), en entorns d'oficina (a ARUP, a Londres) o en sales de control 24 hores (a la sala de control de la refineria de Repsol, a Tarragona), entre d'altres.

Agraïments

La realització d'un doctorat industrial ha estat, en el meu cas, una experiència i un aprenentatge complet: per la realització d'un projecte de recerca aplicada, i també per totes les competències transversals de comunicació, organització i gestió de projectes que he pogut treballar al llarg dels anys. Així, participar del desenvolupament d'un producte des de zero, des de la ideació fins a la introducció al mercat, i veure que l'està fent servir gent de tot el món ha estat una de les millors experiències d'aquests anys. Fer-ho conjuntament amb un equip de companys d'un nivell professional i d'un nivell humà tan alt, fa que la satisfacció sigui doble. Per això, avui em ve al cap molta gent que m'ha acompanyat i m'ha ajudat a llarg d'aquest projecte i a qui vull agrair-ho.

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Aleix, estiu del 2019.

Pròleg

Controlar la llum ha estat un dels principals desitjos i necessitats de la humanitat: des de les primeres fogueres amb llenya i les torxes per cuinar i il·luminar espais quan es ponia el sol, fins a les tecnologies làser més avançades que permeten excitar àtoms o tallar membranes i teixits de forma precisa. La llum evoca emocions i bellesa i és una eina potent que possibilita el desenvolupament de moltes altres tecnologies i investigacions científiques.

D'altra banda, la llum natural, la del sol, sempre ha estat lligada a més salut i benestar. A la dècada de 1880, els científics van descobrir que la llum ultraviolada, una component invisible de la llum del sol, pot matar els bacteris causants de la tuberculosi. Això va fer que la llum del sol s'utilitzés per combatre les malalties que apareixien en els barris baixos i zones urbanes més fosques i es fomentés prendre el sol com a part d'un estil de vida saludable. A dia d'avui encara està àmpliament reconegut per metges i científics que la llum del sol ajuda a combatre malalties, trastorns mentals i a millorar el nostre benestar físic i emocional, però també som cada cop més conscients dels efectes perjudicials que pot tenir la llum ultraviolada sense control, inclòs el risc de càncer de pell.

La llum, identificada amb la raó, també va ser el motor del moviment conegut avui com la il·lustració, en francès *Les Lumières*, i que va donar lloc a pensadors tan importants com Newton, Locke o Voltaire. L'eclosió d'aquest pensament filosòfic, científic i social il·lustrat va estendre's des del segle XVII fins a finals del segle XVIII, anomenat "el segle de les llums", i va obrir la porta a una època de progressos i grans canvis: la revolució francesa, la revolució industrial o l'aparició de l'Enciclopèdia, el primer gran recull dels coneixements científics de la humanitat, entre d'altres. Així, París va esdevenir "la ciutat de la llum", on els visitants quedaven meravellats al veure el que va ser el primer sistema ubrà d'il·luminació del món, i es va difondre la idea d'una ciutat sempre il·luminada.

Al llarg de la història, molts pintors, poetes, filòsofs o científics conscients de la importància que la llum té, han intentat comprendre, explicar, representar i també simular la llum del sol i les seves propietats. Entre els artistes, probablement el pintor valencià Joaquín Sorolla, conegut com el "mestre de la llum", ha estat un dels millors del món en representar escenes amb llum natural a les seves obres. "Odio la foscor", va dir Sorolla. "Els pintors, però, mai no podem reproduir la llum del sol tal com realment és. Només puc aproximar-me a la seva veritat".

Avui, que els ritmes de vida s'han accelerat, que estem més connectats amb tothom però a la vegada passem més temps en espais tancats i hem perdut el contacte amb l'exterior, repensar la llum que ens envolta torna a ser important.

Els últims descobriments en neurociència indiquen que la il·luminació es pot utilitzar per múltiples aplicacions, aportant grans beneficis sobretot en els sectors de la població en situació de més vulnerabilitat: malalts crítics tancats durant setmanes a les UCIs d'hospitals, treballadors de torns de nit que tenen els horaris canviats, o gent gran amb dificultats per moure's i sortir a l'exterior. Repensar i millorar la llum que ens envolta pot proporcionar millors condicions de vida a molta gent, i per això conceptes com "dieta espectral" o "llum circadiària" estan començant a néixer.

Seguint aquesta idea i el camí iniciat per molts investigadors anteriors, en aquest treball hem dissenyat i desenvolupat una font de llum capaç de copiar la llum del sol i imitar les seves propietats espectrals, així com de generar qualsevol altra forma espectral imaginable. Com el pintor, volem aproximar-nos al màxim a la veritat de la llum del sol, per la seva bellesa, per les seves propietats curatives i pel poder que té per fer-nos sentir emocionalment bé.

La il·luminació ha canviat i ja no tornarà a ser mai més estàtica. Avui, arquitectes i dissenyadors busquen cada vegada més crear espais dinàmics, agradables, estimulants i atractius utilitzant noves tecnologies i abandonant les fonts de llum tradicionals i de qualitat més pobra. La il·luminació que ve és dinàmica, ajustable espectralment en tots els colors, en sintonia amb el nostre rellotge biològic, i adaptada a l'aplicació i les necessitats de l'usuari.

Així, aquest treball intenta aportar un granet de sorra per facilitar i accelerar aquest canvi de paradigma, que transformarà la manera que tenim d'entendre la il·luminació, els espais i els seus usos. Un canvi que ja ha començat arreu.

Preface

For centuries, mankind has always tried to create, control, and apply light in many different ways—from the first bonfires and torches to illuminate spaces and objects when sunlight was not enough to the most advanced laser technologies to control atoms or cut membranes and tissues precisely. Light evokes emotions and beauty, and is a powerful tool that leads to the development of many other technologies and scientific investigations.

Moreover, the light from the sun has always been linked to life and well-being. In the 1880s, scientists discovered that ultraviolet light, an invisible wavelength of sunlight, can kill the bacteria that cause tuberculosis. This led to daylight being used to fight illness that flourished in dark urban slums, and to sunbathing being encouraged as part of a healthy lifestyle. Today, it is still widely accepted by medical doctors and scientists that daylight can help to fight diseases, disorders and improve our physical and mental well-being, but we are also increasingly aware of the damaging effects of uncontrolled ultraviolet light, including the risk of skin cancer.

Light, associated with reasoning, was also the start of a movement known as 'Enlightenment', or *Les Lumières* in French, that gave the world scientists and philosophers such as Newton, Locke, or Voltaire. The movement that started in the seventeenth century and lasted till the end of the eighteenth century, known as the 'Century of Lights', opened the doors to an age of change and progress. This is the era that witnessed life-changing revolutions such as the French revolution and the Industrial revolution, and the emergence of the first encyclopaedia, the first compendium of scientific knowledge, among others. Thus, Paris became the 'City of Light', where visitors were amazed to see one of the first urban lighting systems in the world and people had the idea of a city that was always illuminated.

Throughout history, many painters, poets, philosophers, and scientists, who recognized the importance of light, tried to understand, explain, depict, and simulate daylight and its properties. Among artists, probably the Valencia-born painter Joaquín Sorolla, known as the 'master of light', was one of the best in the world to depict sunlit scenes in his works. 'I hate darkness', Sorolla once said. 'We painters, however, can never reproduce sunlight as it really is. I can only approach the truth of it'.

Today, that we are rushing through life, that we are more connected with everybody but spend more time indoors in closed spaces and that we have lost the connection with the outdoors, thinking of light that surrounds us has become important again.

The latest discoveries in neuroscience indicate that light can be used in multiple applications. It can provide great benefits, especially to the most vulnerable segments of the population: critical patients hospitalized for weeks in ICUs, workers who work in night shifts, or the elderly people with problems in moving and walking and who are unable to go outside. By rethinking and improving the light conditions that surround us, we can enrich the lives of many people, and because of that, terms such as ‘spectral diet’ or ‘circadian light’ have started to emerge.

Following this idea and the path found by many previous researchers, in this work we have designed and developed a light source that is able to simulate daylight and mimic its spectral properties as well as generate any other arbitrary spectral shape. As the artist, we aim to approach the truth of daylight at its finest, because of its beauty, its qualities to heal, and the power it has to make us feel good.

Lighting settings have changed and will never be static again. Today, architects and designers are increasingly looking to create stimulating and engaging spaces using new techniques and abandoning the traditional ones with poor qualities. The novel light sources that are appearing are dynamic, spectrally tunable, synchronized with our circadian rhythms, respectful to our biology, and adapted to the end-user needs.

Thus, this work tries to contribute to the acceleration of this change in paradigm, which will transform the way we understand light and its usage—a change that is already happening.

Figure 1: ‘Cosiendo la vela’ artwork painted in 1896 by Joaquín Sorolla. Picture extracted from Wikimedia Commons: https://commons.wikimedia.org/wiki/File:Cosiendo_la_vela.jpg

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Acronyms

CCT Correlated color temperature

CIE International Commission on Illumination

CMOS Complementary Metal Oxide Semiconductor

CRI Color rendering index

CS Circadian Stimulus

EIT European Institute of Innovation & Technology

HCL Human centric lighting

ICU Intensive care unit

ipRGCs Intrinsically photosensitive retinal ganglion cells

IREC Catalonia Institute for Energy Research

LED Light-Emitting Diode

MAPD Mean absolute percentage deviation

PCB Printed circuit board

PID Proportional–integral–derivative controller

PWM Pulse-width modulation

RGB Red, green and blue LEDs

SPD Spectral power distribution

SPIE Society of Photo-Optical Instrumentation Engineers

SSL Solid-state lighting

Chapter 1

Introduction

Light is vital for life. Photons are key for several biological processes among all species, from plants to mammals, and without light, life as we know it would simply not be possible. Moreover, living creatures are synchronised to natural day and night cycles and we are increasingly aware of the benefits of working and living under good lighting conditions.

This introduction aims to give an overview of light and the state-of-the-art of lighting: from natural daylight and its properties, to the technology and the science behind the most common artificial light sources and the development of the last advanced systems. Finally, the objectives of this work and the motivation are also provided and discussed.

First, in section 1.1 we will see how to measure light and how to quantify its properties, introducing some of the basic indicators that will be used later along the manuscript.

Then, we will explore the qualities of natural daylight and we will discuss the knowledge we have today about how does light affect our body and brain (section 1.2).

After that, we will show the most used lighting technologies in developed countries and how do they compare with daylight (section 1.3).

Later, we will discuss the state-of-the-art of spectrally tunable lighting systems (section 1.4): its origin, its limitations and the potential applications.

And finally, we will discuss the overall objectives of this work, the motivation and the framework and partners involved (section 1.5).

1.1 Measuring and quantifying light

In physics, light is usually referred as electromagnetic radiation of any wavelength. However, in lighting, light is usually referred to only electromagnetic radiation in the visible range (from 380 nm to 780 nm).

To talk about light and its properties, several indicators are used by the scientific, architecture and lighting designers community. The aim of this section is to give a brief overview of these indicators that will be used later along the manuscript. They will help us describe light in terms of its visual functions: chromaticity, illuminance and quality; and its non-visual functions: melanopic lux and the influence it may have in our brains.

Below, the reader can find a succinct description of the main and most important indicators for light and lighting.

1.1.1 Spectral fidelity

The power (W) per unit of wavelength of a light source is called the spectral power distribution (SPD), also known as the spectrum of light. Almost all the properties that any kind of light has are ultimately derived from its spectral shape: colour, quality or non-visual effects, all are consequence of the SPD. It is the full physical signature of any lighting process (except for the polarization of light or the spatial shapes of the light beam and other geometrical effects).

The error function used to assess the spectral fidelity between two normalized spectra A (target SPD) and B (test SPD) is the mean absolute percentage deviation (MAPD), measured for each wavelength j, and defined by Eq. 1.1 for a system of K wavelength points:

$$MAPD = \frac{100}{K} \sum_{j=0}^{K} \left| \frac{S_j^A - S_j^B}{S_j^A} \right| \tag{1.1}$$

This error % tell us how similar are two spectral shapes, being 0% if they are identical and bigger when they are different.

1.1.2 CIE 1931 xy colour space

The CIE 1931 XYZ color space was created by the International Commission on Illumination (CIE) in 1931 [2]. In this color space, the color points are calculated using the CIE 1931 Standard Observer Colour Matching Functions ($\overline{x}(\lambda)$, $\overline{y}(\lambda)$ and $\overline{z}(\lambda)$) as indicated in equations 1.2, 1.3 and 1.4.

$$X = \int_{380}^{780} S(\lambda)\overline{x}(\lambda)d\lambda \tag{1.2}$$

$$Y = \int_{380}^{780} S(\lambda)\overline{y}(\lambda)d\lambda \tag{1.3}$$

$$Z = \int_{380}^{780} S(\lambda)\overline{z}(\lambda)d\lambda \tag{1.4}$$

where $S(\lambda)$ is the SPD of the light source.

Knowing this XYZ values, the small xy color coordinates can be easily derived:

$$x = \frac{X}{X+Y+Z} \tag{1.5}$$

$$y = \frac{Y}{X+Y+Z} \tag{1.6}$$

These coordinates, called the chromaticity coordinates, define the x, y, Y colour space that is the basis for representing colours in modern colour science.

1.1.3 CIE 1976 u', v' colour space

The CIE 1976 L*, u*, v* (CIELUV) color space (u', v') is a transformation of the 1931 CIE xy colour space that aims to provide a more perceptual uniform representation of the visible colour gamut [2]. The CIE xy coordinates can be converted into the (u', v') system with equations 1.7 and 1.8.

$$u' = \frac{4x}{-2x+12y+3} \tag{1.7}$$

$$v' = \frac{9y}{-2x + 12y + 3} \tag{1.8}$$

1.1.4 Colour difference

The colour difference between two light sources is usually assessed using the CIE 1976 L*, u*, v* (CIELUV) colour space (u', v'), since it is more uniform and is a well-accepted metric for assessing the chromaticity of solid-state lighting (SSL) products [3].

In this space, the color difference between two colour points (u'_A, v'_A) and (u'_B, v'_B) is an Euclidean distance, defined by eq. 1.9:

$$\Delta u'v' = \sqrt{(u'_A - u'_B)^2 + (v'_A - v'_B)^2} \tag{1.9}$$

1.1.5 Colour quality

Objects change their appearance depending on the type of illumination used. The final colour of an object is calculated from the product of its reflectivity spectrum and the spectrum of the light source used. While daylight is considered the best light setting to render objects, low quality light sources can render colours very poorly and completely change its 'natural' appearance.

The General Colour Rendering Index (CRI Ra) [4] was introduced in the middle of the 20th century by the CIE comittee. The CRI Ra is based on the colorimetric comparison of a number of samples from the Munsell Colour System with a standard light source. Its maximum value is 100, meaning that the light source under test renders colors like a standard reference light source. It can be as low as 0 for extremely bad light sources or even negative.

Although the CRI Ra is a widely used by the industry and accepted metric to characterize the colour rendering properties of light sources, it has some limitations because it uses a small set of Munsell samples. Recently, other metrics and indices appeared, such as the IES TM-30-15 (see [5]).

The TM-30-15 method uses three indicators to evaluate a light source: a fidelity index (Rf) (for colour quality), Gamut index (Rg) (to evaluate the saturation) and Color Vector Graphic (CVG) (as a graphical visualization). The fidelity index Rf, that goes from 0 to 100, is an improved version of the CRI because it uses 99 colour evaluation samples instead of just 8 (with strong metameric problems).

1.1.6 Luminous flux

The luminous flux of a light source measures the perceived power of light usually expressed in lumens (lm). The luminous flux can be calculated using equation 1.10:

$$\phi_v = 683 \int_{380}^{780} V(\lambda)S(\lambda)d\lambda \tag{1.10}$$

where $V(\lambda)$ is the CIE spectral luminous efficiency curve for photopic vision [6] and $S(\lambda)$ the SPD of the light source.

1.1.7 Illuminance

The luminous flux per unit area received by a surface is called the illuminance and is expressed in lm/m^2 or more commonly in lux (lx). The illuminance determines how bright an illuminated surface is perceived and is one of the main units used by lighting designers and architects. It can be derived from the luminous flux using equation 1.11:

$$E_v = \frac{d\phi_v}{dA} \tag{1.11}$$

1.1.8 Melanopic lux

It is now widely acknowledged that light does not only play a visual function to see objects and scenes around us, but it also has a non-visual function. In section 1.2.1 we explain these non-visual functions and how does light influences our brain.

The effectiveness of a given light spectrum in activating this non-visual pathway in the brain depends on the melanopic action spectrum (than can be represented by the melanopic lux), or by other complex indicators (such as the Circadian Stimulus (CS)).

The melanopic lux can be derived from the spectral power distribution of a light source weighted by the melanopsin spectral sensitivity function [7] and integrated over wavelength. It can be calculated using equation 1.12:

$$M_{lux} = 72983.25 \int_{380}^{780} M(\lambda)S(\lambda)d\lambda \tag{1.12}$$

where $M(\lambda)$ is the normalized melanopic sensitivity curve and $S(\lambda)$ is the SPD of the light source.

The full description and development of equation 1.12 can be found in [8].

Similar to melanopic lux, the Circadian Stimulus (CS) indicator developed by the Lighting Research Center [9] describes the model of spectral irradiance for the human circadian system. Therefore, it is also used to describe the effectiveness of a light source for the circadian system, as measured by nocturnal melatonin suppression.

1.2 Daylight and its interaction with the brain

We live on a small and fragile planet that revolves around the sun. This simple fact gives us light and darkness. It allows for seasons to change, determines the length of a year, and has profound effects on our well-being.

The sun is mainly composed of hydrogen and helium, and it is a giant sphere of hot plasma powered by nuclear fusion. It has a surface temperature of 5778 K and is considered to be an almost perfect blackbody radiator.

The atmosphere filters radiation from the sun, including sunlight, and the radiation that reaches the surface of the earth is primarily between 200 and 4000 nm. What we call ‘natural daylight’ is visible radiation and is the result of an interaction between sunlight and the atmosphere. The duration of daylight is dependent on the location of a place on Earth and the time of year.

Daylight is far from static, and the spectral aspects of daylight can change in a single day. The SPD of daylight measured at 10 am (9 April 2019) on the rooftop of an office building in London, the United Kingdom, is shown in Fig. 1.1. It had a CCT of 5800 K and an illuminance of approximately 5000 lx.

Daylight transitions during the day, and the changes in colour and illuminance are a result of small spectral changes due to variations in the atmospheric conditions. The sun’s altitude, as well as clouds, fog, pollution, humidity and other meteorological factors may affect the absorption of some wavelengths of solar radiation modifying the SPD and illuminance of sunlight.

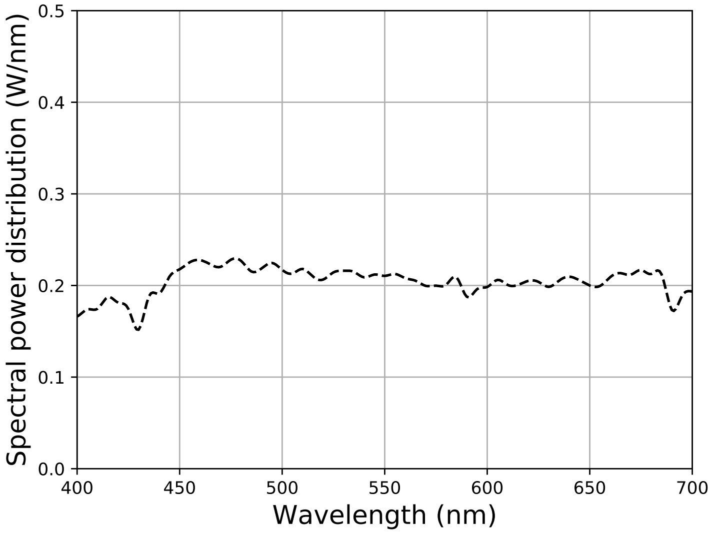

Figure 1.1: Daylight SPD measured outdoors, at 10 am in London, United Kingdom (April 9th, 2019).

On the same day and from the same location, the spectrum of daylight can evolve over time, as shown in Fig. 1.2. The CCT changed to 5500 K and the illuminance increased to above 15000 lx (three times as high as before).

The whole evolution of daylight at that specific location is shown in Fig. 1.3, 1.4, and 1.5. Figure 1.3 shows the changes in CCT with a maximum at 8 am at 6250 K and a minimum at 4 pm at 5250 K. The CRI Ra (see Fig. 1.4) was above 90 throughout the period over which the measurements were conducted.

The illuminance values of daylight for a day that had a very foggy and cloudy morning with some raindrops, and a sunny afternoon with a clear sky, is shown in Fig. 1.5. The weather conditions correspond with the low lux values recorded during the early hours of the day and the high illuminance recorded after 2 pm.

In summary, what we deem as natural daylight is a dynamic product of the light from the sun and its interaction with the sky in a specific setting. This combination creates light with unique properties such as the energy at different wavelengths, variable illuminance values, and an outstanding quality of colour of the objects around us.

Humans overwhelmingly prefer living and working in places with access to daylight. However, nobody fully understands or knows why. One of the reasons could be that our bodies, including our visual system, have evolved under daylight

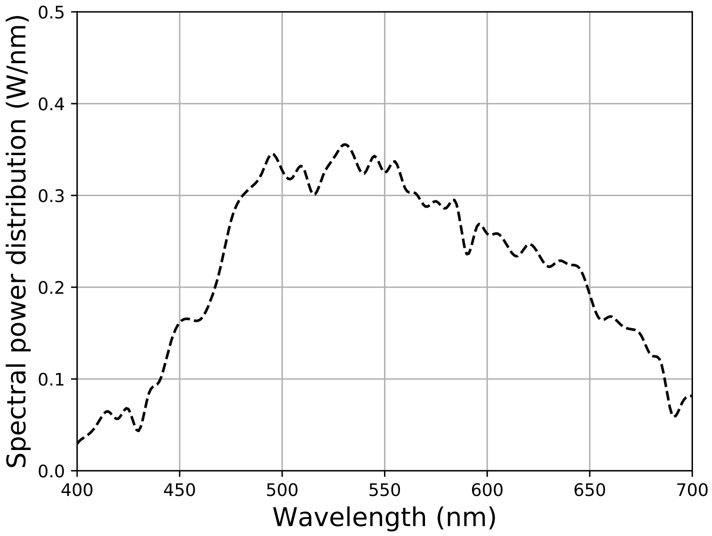

Figure 1.2: Daylight SPD measured outdoors, at 4 pm in London, United Kingdom (April 9th, 2019).

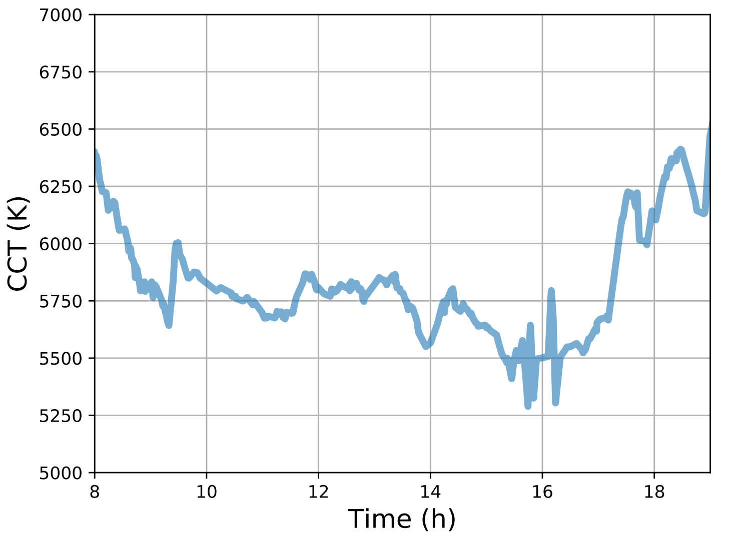

Figure 1.3: Measured CCT values of daylight in London, United Kingdom (April 9th, 2019).

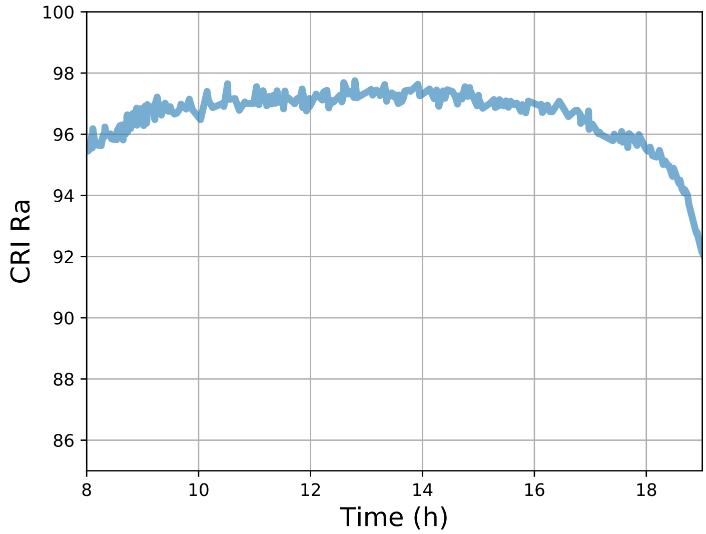

Figure 1.4: Measured CRI values of daylight in London, United Kingdom (April 9th, 2019).

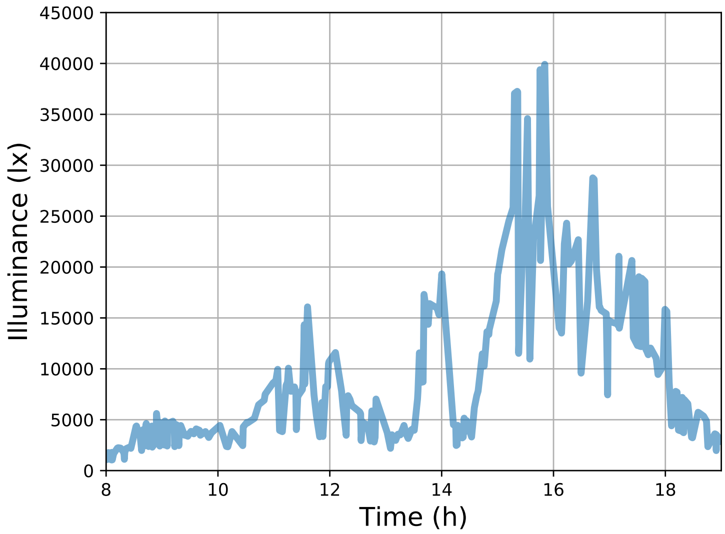

Figure 1.5: Measured illuminance values of daylight in London, United Kingdom (April 9th, 2019).

for several millennia. Daylight allows us to see without the aid of artificial light and allows for a variety of stimuli, and it is widely accepted that access to daylight reduces stress and increases productivity.

The use of artificial lighting began a few centuries ago, and artificial lighting technologies have improved over time. This has allowed us to be able to perform activities inside buildings and has led to an extension of our active time. This has consequently shortened the time we are exposed to natural daylight on a daily basis.

Several recent studies have drawn a link between limited or inadequate exposure to daylight and certain medical conditions. Myopia, for example, is considered as an epidemic in some Asian countries (affecting more than 90% of the teenagers and young adults in China), and some studies suggest that it is caused by limited exposure to daylight during childhood [10]. Sunlight plays a key role in the development and treatment of disorders such as seasonal affective disorders (SADs), depression, and different types of insomnia [11]. In an office settings, windowless environments have a negative impact on the well-being, sleep quality, and productivity of workers, in comparison to environments with more daylight [12].

From a neuroscience point of view, we now have a better understanding and knowledge about light and its influence on our body and brain.

1.2.1 Non-visual effects of light

For years it has been known that light influences our brain and behaviour but it was not clear how. However, around 20 years ago, the discovery of the photopigment melanopsin [13] was key to understand the mechanism underneath [14] [15]. In the human retina, melanopsin can be found in a subset of retinal ganglion cells, the intrinsically photosensitive retinal ganglion cells (ipRGCs). Besides cones and rods, this photoreceptors also carry information about light.

Photopigments like melanopsin are characterised by their spectral sensitivity, the dependence of their response amplitude to lights of different wavelengths. Melanopsin sensitivity peaks at 480 nm [7], midway between the short- and middle-wavelength cones, but is broad-band and overlaps with that of all four classical photoreceptors. This means that almost any light can lead to a melanopsin-encoded signal if it is bright enough. Fig. 1.6 (left) shows the spectral sensitivity functions of the four classical photoreceptors and the sensitivity function of melanopsin.

However, before light reaches the ipRGCs, it passes through the cornea, lens and ocular media. This filtering alters the amount of light arriving at the retina [16]

[17]. The lens specifically attenuates blue light and its density increases with age, indicating that young people may get higher doses of blue light in the retina than older people from the same light source.

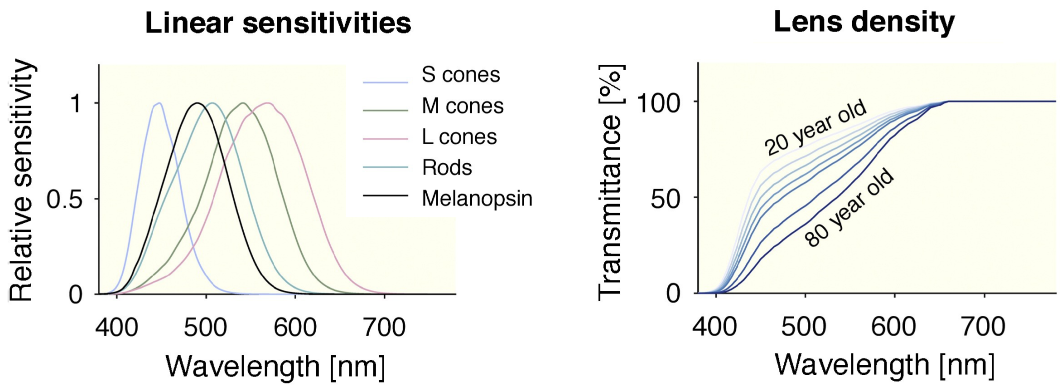

Figure 1.6: (left) Spectral sensitivity functions of the four classical photoreceptors (S cones, M cones, L cones and rods) and melanopsin. (right) Pre-receptoral filtering due to lens aging. Figures extracted from [1].

At the present time, the melanopsin contribution to visual and non-visual functions are still under investigation, but some key issues are well accepted [1].

Melanopsin-mediated signals have a profound influence on our physiology and behaviour. It is the origin of the non-visual pathway that entrains biological rhythms and the light/dark circadian cycle [18] [19]. Moreover, they are also responsible for regulating our body temperature, melatonin suppression, attention, mood, heart rate, sleep and electroencephalographic dynamics [20] [21] [22] [23].

The production of melatonin, a hormone naturally produced by the body during the evening and night, is suppressed by light via the retinohypothalamic pathway connecting ipRGCs to the suprachiasmatic nucleus (SCN) [24]. This hormone helps us feel tired and sleepy at night. The spectral sensitivity of melatonin suppression showed to be inconsistent with cone and rod sensitivty functions, and importantly, in some functionally blind people with no measurable cone and rod functions, light also suppresses the production of melatonin [25] [26].

In addition, our body follows a circadian rhythm which is synchronised to the external light-dark cycle via the retinohypothalamic pathway. Although it has long been known that the entraining light signal emanated from the retina [27] [28] it was not until the discovery of the ipRGCs and the characterisation of the melanopsin photopigment they contain that the importance of spectral variations in light for eliciting non-visual effects was fully recognised. It is widely accepted today that exposure to some light at night can shift the circadian rhythm by minutes or hours

[29]. This shift can be either a phase delay or a phase advance, depending on the timing of light exposure [30] [31]. Melatonin suppression and circadian phase are separable and functionally decoupled systems, with neither being a trigger for the other, but both related to melanopsin signals [32].

Still today, lighting installations in offices and buildings are specified in terms of their effects via the classical visual pathway (e.g. chromaticity and lux levels). However, this emerging evidence shows that this is not enough and it is also important to consider the non-visual effects of light. Lighting designers, architects and building engineers need to take into account the non-visual pathway of light when aiming to design spaces and environments respectful to our biology. Probably the first step is to start talking spectral, accepting that the whole spectral aspects of light are necessary (i.e. the spectral power distribution of light), and not only classical lighting indicators such as CCT, CRI and illuminance values. Then, the development of multi-channel LED lighting systems will provide the essential technology to enable the shift to a truly spectral lighting paradigm.

1.3 Traditional lighting technologies

Bonfires, the candle and other gas flammable lighting methods were the first light sources used when natural light was not enough. But after the invention of electricity, new methods appeared.

Today, the most used artificial lighting technologies in developed countries are fluorescent lamps, RGB light sources and white or tunable-white LEDs.

The first ones, fluorescent lights, are based on the principle of a gas discharge combined with a wavelength-converter. Two thermionic electrodes are preheated to generate electrons within the tube. A high voltage pulse then ionises the gas inside the lamp heating up a small amount of mercury. A phosphor coating converts the invisible ultraviolet radiation into visible wavelengths. The spectral properties of fluorescent lamps are defined by the mercury energy lines and the composition of the phosphor coating on the inside of the discharge tube. A typical SPD of a fluorescent lamp compared to daylight is shown in Fig. 1.7.

Because of its spiky spectrum lacking energy in most of its wavelength components, fluorescent lamps are considered very poor quality light sources. The CRI Ra is usually below 80. The efficiency depends on the materials used, but it is around 50 lm/W.

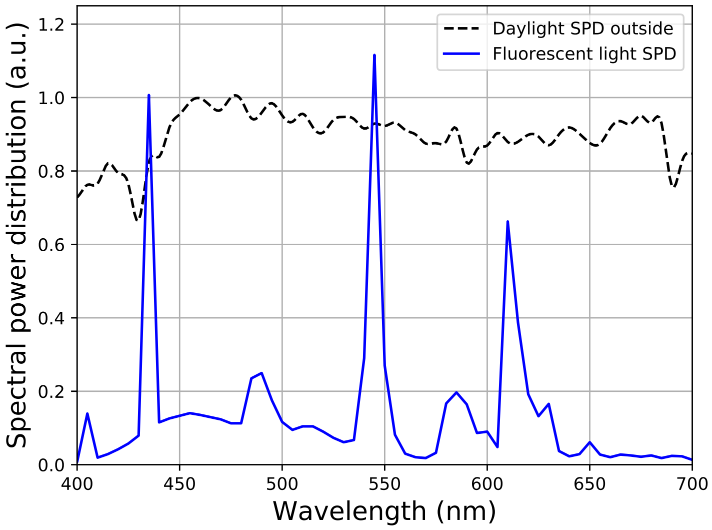

Figure 1.7: Measured daylight SPD (black dashed line) compared to a commercial fluorescent lamp SPD (blue line).

However, new and more advanced technologies are taking the lead.

Today, solid-state lighting (SSL) solutions are fully compatible with current digital systems and information technology. Light-emitting diodes (LEDs) are today present in a wide range of wavelengths across the visible and IR regions, showing fast time responses (in the microsecond range). In addition, LEDs present narrow emission bands (typically about 20 nm), low power consumption, long lifetimes, and good dimming capabilities [33]. This has allowed the development of LEDs in different parts of the spectrum.

RGB light bulbs are made combining three types of LEDS: a red, a green and blue one, all packed together to form a compact semiconductor light source with a tunable colour point. By modulating the amplitude of each LED, different colours can be created. The spectrum is shown in Fig. 1.8 and is compared to daylight spectrum. The CRI Ra is around 60 and the efficiency is around 80 lm/W (although these values change depending on the channel amplitudes).

White LEDs are created with a blue LED and a yellow phosphor, and by changing the properties of the phosphor coat, different kinds of CCTs can be designed. Moreover, the most simple and cheap tunable-white LEDs are created by combining two types of white LEDs: a cool white LED together with a warm white LED. Modifying the intensity of each LED, the CCT can be controlled and adjusted externally. Fig. 1.9 shows the SPD of a tunable-white LED compared to daylight. In this case the CRI Ra can reach higher values, above 75, and the efficiency is also

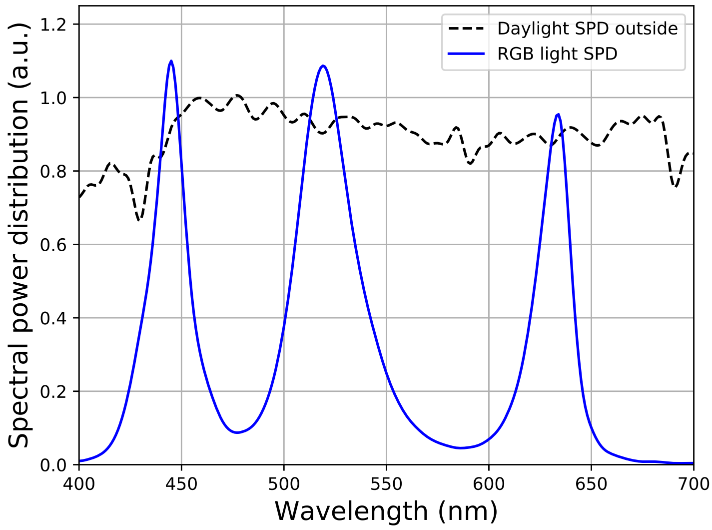

Figure 1.8: Measured daylight SPD (black dashed line) compared to a commercial RGB light SPD (blue line).

usually above 100 lm/W.

The spectral fidelity between different light sources can be assessed with the MAPD percentage (see Eq. 1.1) and the results are shown in Table 1.1. Using this indicator, we can see that a fluorescent lamp SPD reaches an 85% error when compared to daylight at 10 am. Similarly, an RGB light source reaches 65% and a commercial tunable-white solution has a MAPD error around 32%, although this values can change a little depending on the materials used.

Test light source	MAPD
Fluorescent lamp	85
RGB light	65
Tunable-white	32

Table 1.1: MAPD percentage between the target (daylight at 10 am) and the different light sources emitted SPD.

Visually, the comparison is shown in Fig. 1.7, Fig. 1.8 and Fig. 1.9.

It is clear that classical artificial lighting technologies have spectral properties very different from natural daylight. In fact, such technologies only deal with chromaticity properties, illuminance or CCT, and do not talk spectral (their properties are specified in terms of their effects via the classical visual pathway). Although in those systems some parts of the spectrum are dimmable, we cannot consider

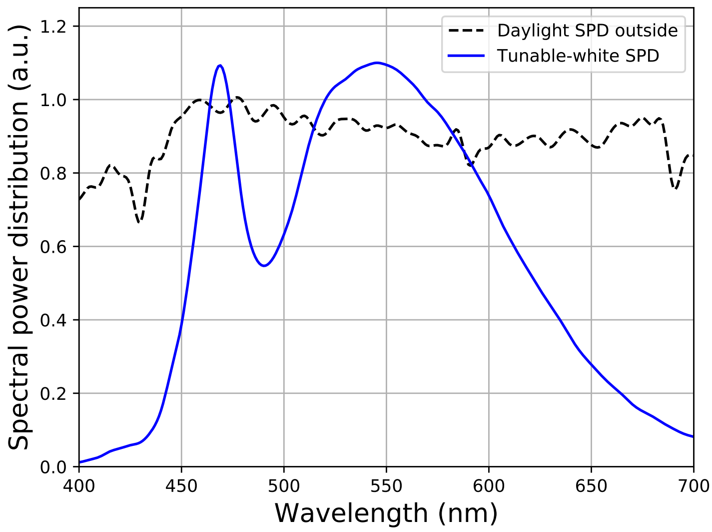

Figure 1.9: Measured daylight SPD (black dashed line) compared to a commercial tunable-white SPD (blue line).

them as spectrally tunable because, for example in an RGB light source, with only 3 color channels it is not possible to create many different spectra, or the spectral fidelity is extremely poor (see Table 1.1). The same happens for white or tunable-white LEDs, that are static or only useful to create different CCTs, regardless of the spectral shape.

Therefore, these light sources have very limited applications (only for static general lighting or to create colours) and are poor tools to enable a dynamic spectral lighting paradigm, to entrain our circadian rhythms, modify the perception of objects or influence other cognitive processes. To do so we need full spectral light sources that will bring a new world of opportunities.

1.4 Spectrally tunable lighting systems

As we have seen, the spectrum of light is the full physical signature of any lighting process. Before the advent of SSL, it was only possible to have light sources provided with fixed spectrum, determined by the physical properties of the materials involved in the emission processes. Today, SSL technology offers a completely new paradigm associated with the possibility to mimic any light spectrum imaginable and also to create new spectral shapes not found in nature. By combining several coloured LEDs together in a packed PCB, the resulting smart device is externally controllable, and is able to sculpt different SPD depending on the end-user needs. This spectral optimization gives rise to a full range of potential applications where specific spectral components play an important role.

Although spectrally tunable lighting systems, also known as multi-channel LED lighting systems, have been here for some time now, its usage is still far from mass adoption. Actually, all spectrally tunable lighting systems developed in the past were used only for scientific purposes and some of the first early adopters of this technology were researches working with solar simulators, colour and vision scientists, or neuroscientists studying the connection between light and the brain.

For example, the fist laboratories to develop a spectrally tunable lighting system were Fryc et al. [34] in 2005 at the National Institute of Standards and Technology (NIST). They developed a light engine with 35 LEDs to match CIE standard illuminants. Using an optimization process based on partial derivatives, they were able to calculate the best match to a target illuminant. However, the method had a very large computing time. Others, like Kolberg et al. [35] developed an LED solar simulator with the ability to modulate certain wavelengths. Tan et al. [36] implemented a wireless control for lighting systems that demonstrated high energy savings and Burgos et al. [37] developed a spectral LED-based tunable light source to study its potential applications in colour science. More recently, Chew et al. [38] developed a spectrally tunable lighting system with eight channels and a closed-loop control.

In the marketplace, there are only a few companies developing spectrally tunable solutions. One example is the Telelumen Light Replicator developed by the company Telelumen in US [39], and made of 16 different LED channels. Another company is Thouslite in China [40], that has developed the LEDCube, a light engine with 11 channels (see Fig. 1.10 (a)). Finally, Gamma Scientific [41], also in US, developed a light engine with 35 channels for microscopy, fluorescence and other research techniques (see Fig. 1.10 (b)). All these light engines aim to tackle a research and scientific market and are not designed to be installed in a general lighting setting. Actually, the price for a single unit in all of them is above 15.000$ and they are big in size, heavy and most of them are rather slow (usually 1 second response time), and without any kind of optical feedback control to monitor the emitted light and prevent spectral drifts or ageing of the LEDs.

If spectrally tunable lighting systems have already proved to be a superior lighting technology with great benefits for different applications [42] [43], why its usage is still marginal and only adopted by a niche research community? Potential reasons for that are its price, rather expensive compared to traditional lighting

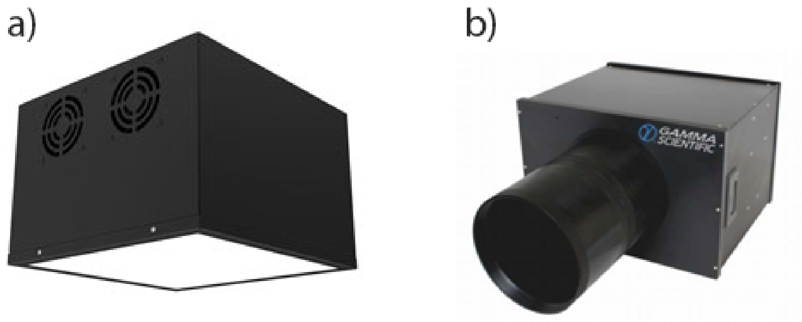

Figure 1.10: (a) The LEDCube, a spectrally tunable light engine developed by Thouslite. (b) Spectrally tunable light engine developed by Gamma Scientific.

systems, and the fact that some obstacles, technical challenges, need to be overcome before the different parts combine into a mainstream technology.

One obstacle has to do with the fact that natural daylight always implies dynamism. Daylight changes over the course of the day, which from a product development perspective, the varying signals applied to the LEDs lead to a distribution of different junction temperatures. LEDs are made of semiconductor materials, they are very sensitive to temperature variations and change their emission peak wavelength and intensity. If temperature effects are not properly accounted for the spectral accuracy can be compromised, and also the associated colour variations are easily perceived to the naked eye. All these effects need to be corrected in order to end up having a technology that aims at competing with the current standards of the lighting industry.

As pointed out by Burgos in 2016 [44], "the ideal spectrally tunable light source would be mainly capable of simulating any kind of illuminant, standard or customised, in a fast way as when using minimization algorithms; reproducing accurately target illuminants by means of a high density of spectral narrow bands; and generating a total radiant/luminous flux that could be regulated depending on the application without spectral shifts". He finally concludes: "All these needs are not met by any light source, yet".

But how can this be done in an optimal and efficient way? And moreover, how can this be done without a significant cost increase?.

For general lighting, it is clear that the possibility to mimic daylight spectra can bring enormous benefits in terms of circadian properties, mood and well-being (section 1.2.1). Beyond that, there are important applications where emulation of natural light can be critical. The medical sector needs very high colour rendering, but without ultraviolet or infrared content (i.e. surgical applications). Museums need very specific, standardized light sources for safely, yet vividly, illuminating collections [45] [46] [47]. Hybrid lighting, combining daylight with artificial sources in order to provide uniform illumination over an arbitrary period of time [42], can benefit significantly. There are also specialized needs in graphic arts, photography and cinematography.

The majority of the traditional lighting market is today unaware of the technological progress achieved and they are still stuck with old and classical systems. However, some lighting designers followed the new trend and are today struggling with a redefinition of its very own language, one that incorporates the ever-growing scientific evidence of the influence that dynamic light has on animals and biological species.

ARUP, for example, is one of these architecture, engineering and design companies leading the transition towards healthier living environments. They have a clear strategy about circadian lighting and they are fully aware of the benefits of controlling and modulating the spectrum of light for human centric lighting applications [48]: "A circadian lighting strategy is one where lighting design supports the human diurnal need for illumination and darkness cycles in tune with their circadian system. This strategy should include both natural and artificial lighting and should take into account the changes in colour spectrum, intensity and directionality over the course of a day".

Enabling advanced spectrally tunable lighting systems in the general lighting market is far from trivial and as pointed out before, several technical challenges need to be surmounted. Yet, the new and unexplored world of possibilities that opens up is stimulating and motivating.

For the first time in the history of artificial lighting technologies we can have full spectral control of light, and as other breakthrough technologies, we are still unaware of the whole set of applications it may enable.

However, some of those applications are today very clear:

1. Enabling the shift to a truly spectral lighting paradigm, where the spectrum of light is as important or more than other indicators such as CCT or CRI. This allows lighting designers to work together with neuroscientists and create light sequences based on the SPD of light.

   For example:

   (a) Designing lighting systems for office settings to boost alertness and mood of workers. It is widely accepted that windowless environments have negative effects on workers' mood and productivity. Thus, designing more engaging and stimulating environments can lead to better performance and comfort. The same apply for schools or universities: a correct light can stimulate students' attention, maximize knowledge absorption, lead to better sleep at night and improve social interaction.

(b) Designing lighting systems for Hospitals to entrain circadian rhythms and improve the well-being of patients for a fast recovery. This is specially important in windowless Intensive Care Units (ICU) where patients are in extreme bad conditions, unable to move and connected 24/7 to machines. Providing a lighting system that simulates daylight changes, sunrises and sunsets, can be very positive for the brain and speed up the recovery time.

(c) 24/7 working environments that are deprived from sunlight are particularly vulnerable to shift work disorders with a negative impact on workers' health and productivity. Control rooms usually lack daylight, operate 24 hours a day, and workers perform critical tasks (for example in oil refineries, nuclear power plants or transportation facilities). A good designed lighting system could impact the concentration and the alertness of workers, leading to less errors, and it can be possible to adapt the indoor lighting to the circadian rhythms of night-shift workers.

(d) Bringing daylight properties to northern countries (Norway, Finland, Iceland, Canada...) when in winter the lack of natural daylight is a major cause of seasonal depression and tiredness.

2. Create a light setting optimizing the SPD for colour fidelity, or to boost a specific colour saturation, or any other indicators in order enhance specific colours, pigments or the perception of objects. The combinations are endless:

   (a) These properties could be used by museums to represent artworks in a completely new way. Transforming the visitors experience by optimizing the visual perception of colors, recreating atmospheres and preserving heritage and controlling the damage potential of the light spectra being used.

   (b) For surgery, to help doctors identify damaged tissues or blood vessels. This could be done using high colour quality light (CRI Ra $>$ 95) or by designing spectra in a way that enhances or saturates specific colours.

3. Digital parametrization of spectral light [49]. Designing light spectra, sharing, recording and playing dynamic light sequences among others. For different

sectors:

(a) Leisure, for household environments. Customizing light spectra for your needs.

(b) For professional photography and video makers. Designing light spaces is key for media arts and cinema, evoking emotions and having complete control over the scene.

(c) For graphic arts, colour calibration, printing and textile industries.

4. For research: Spectroscopy, microscopy, medical sciences, biology, photonics, colour science and other scientific fields can take advantage of full spectral control systems [50].

In summary, spectrally tunable light engines are a breakthrough technology and are called to be the future of indoor lighting. Many industries and markets could benefit of having industrial cost-effective devices able to bring a full spectral control of light, and this is what this project aims to deliver.

In the next section we underline the technical objectives and the aims of this thesis, as well as the context where this work has been developed.

1.5 About this research project

1.5.1 Hypothesis and objectives of this work

This work aims at developing unrivalled spectrally tunable lighting systems. Previous research works helped to prove how this technology could be beneficial for many different areas and markets, but at the start of this project the only end-users of this technology were a niche scientific community.

However, multi-channel LED light engines are good candidates to satisfy the demand that a shift to a truly spectral lighting would imply. But the problem that we are facing here is multiple: (i) how can multi-channel LED sources, where every channel has its own temperature dependency and aging mechanisms, warrant spectral and colour stability over their lifetime? And (ii) how can this be done without a significant cost increase?

Yet, is it possible to improve the state-of-the-art spectrally tunable lighting systems and to speed up this transition towards a general lighting mass market?

Can these devices, still only used by researchers, be accepted by hospitals, offices or museums to improve their light quality and the overall experience offered?.

Taking everything mentioned into account, this project will conduct research in new spectrally tunable lighting systems with added intelligence and sensing means. The final goal of the project is to build a method and device based on multi-channel LED light engines to generate arbitrary spectra with excellent accuracy in an industrial way.

Therefore, the design, development and implementation of several spectral control methods to be used in multi-channel LED light engines are in the scope of this research. Moreover, the results will be tested and validated in several different applications and environments that will help to accelerate the transition from a research oriented device towards a lighting mass market product.

The main objectives of this work are:

1. Improvement of the state-of-the-art of multi-channel light engines and design and optical development of a cost-effective industrial version with good colour mixing, thermal management and light control.

2. Design and implementation of spectral control methods for multi-channel LED light engines to efficiently and precisely generate arbitrary spectra.

   As it has been said, this device will be able to generate arbitrary spectra by tuning the different LED channel weights and finding those that minimize the MAPD error. Thus, the first part will be devoted to the calculation of the weighting amplitudes that best match a target spectrum in a fast and precise way.

   Once the weighting amplitudes for the target spectrum have been calculated, a second part will be devoted to new control systems designed to fine-tune the weighting amplitudes to compensate for small spectral changes in the LEDs, primarily as a consequence of thermal junction variations or aging of the LEDs.

   More specifically, the particular objectives to be achieved in this project are listed below:

   (a) Design and implementation of several algorithms to effectively and precisely calculate the LED channel weights that minimize the error for a given target spectrum.

   (b) Design and implementation of spectral feedback control systems using external sensors to compensate for small spectral changes in the LEDs due to temperature changes or wear-out of the LEDs.

Two kind of sensors will be used: a low-cost miniature spectrometer adapted inside the tunable LED light source that can collect a small fraction of the emitted light, and a colour sensor also adapted inside the light engine. Both devices will be used separately as feedback means.

Thus, the main goals in this section are:

i. Design and implementation of a close-loop feedback control system with a low-cost miniature spectrometer adapted inside the light engine.

ii. Design and implementation of a close-loop feedback control system with a colour sensor adapted inside the light engine.

3. Testing and validation.

The light engine was tested under different conditions and environments. This includes the installation of the newly made LED light engines in some selected locations, and it also includes two different operational modes: the use of predefined dynamic light sequences, or a real-time daylight spectral match to bring natural and circadian properties inside as they are measured outdoors.

More specifically:

(a) Installation and validation of the lighting system in special 24/7 control rooms.

(b) Installation and validation of the lighting system in Hospitals.

(c) Installation and validation of the lighting system in a real office setting.

1.5.2 Context and framework of this project

This work has been developed in close collaboration between two partners: the company Ledmotive Technologies S.L. and the research center Institut de Recerca en Energia de Catalunya (IREC), at the present time both located in Jardins de les Dones de Negre 1 Pl. 2, 08930 in Sant Adrià de Besòs (Barcelona).

The project did not start from scratch. In fact, it naturally followed the path started by previous researchers, engineers and scientists, that helped together to build the foundations and knowledge that Ledmotive and IREC successfully created.

Moreover, IREC and Ledmotive have the equipment and laboratories where most of the measurements took place. We extensively used their outstanding facilities and high-end devices such as integrating spheres (ISP 500 and ISP 2000 by

Instrument Systems), spectrometers (CAS 120 by Instrument Systems), luxometers (Konica Minolta), etc.

Furthermore, the Universitat Politècnica de Catalunya (UPC) and its professors and professionals always provided us with all the help and support needed for a successful development of this thesis.

Besides this three partners, this research project has also been backed by the KIC InnoEnergy, a European Union organization that supports research with impact. InnoEnergy, that is part of the European Institute of Innovation & Technology (EIT), not only supported us with resources and excellent training through their PhD School, but it also helped us to promote our work and to build a network of highly skilled contacts and friends spread around the world.

Additionally, during the third year, I was able to carry out a research project between the cities of London and Newcastle upon Tyne, in the United Kingdom. During my mobility stay there, we worked together in a three-fold collaboration between Ledmotive, the Newcastle University's Institute of Neuroscience and ARUP. We designed and implemented a novel experiment and set-up in ARUP to understand which spectral variations in illumination would be appropriate to achieve particular human responses. There, having full access to all the services, facilities and experienced professionals working at ARUP and at Newcastle University was extremely useful and stimulating.

Finally, the Government of Catalonia through the agency AGAUR (Agència de Gestió d'Ajuts Universitaris i de Recerca), and the Spanish Ministerio de Economía y Competitividad (MINECO), provided the essential resources necessary to work on this project for a full time, to attend worldwide conferences and events, and to buy all the materials and equipment.

Chapter 2

Global discussion on the results and conclusions

Six scientific publications are presented in this thesis [51] [52] [53] [54] [55] [56]. The global objective of these publications is to develop spectral control methods for multi-channel LED light engines and to prove that they can be used in real-life applications.

Achieving these goals require different steps: First, designing and developing different light engines with good optical mixing and thermal management. Second, implementing spectral algorithms in the firmware to calculate the channel amplitudes that give the best fitting to a target spectrum in a fast and precise way. Third, ensuring that the spectral shape and colour remains stable and accurate using a close-loop feedback system and a set of light sensors. Finally, the system needs to be validated for different applications. In this chapter we summarize the results achieved and discuss its conclusions.

2.1 Two light engines for two different worlds

During this PhD research project we developed different kinds of light engines, some of them ended up as early prototypes and some of them ended up as final products to be sold. At the present time, the light engines that reached a stable production line are two, with different spectral properties and aiming to tackle different markets and needs: the SPECTRA TUNE LAB for scientists (see datasheet in B.1), and the VEGA 07 for a general lighting mass market (see datasheet in B.2).

2.1.1 The SPECTRA TUNE LAB: a light engine for scientists

The SPECTRA TUNE LAB was the first light engine developed after several prototypes and research efforts. It is composed of 48 commercial monochromatic LEDs (from Lumileds Luxeon C[57]: Deep Red, Red, Amber, PC Amber, Lime, Green, Cyan, Blue and Royal Blue; and from Lumileds Luxeon Z UV[58]: 425–430) arranged in 10 individual channels (a channel should be regarded as an arrangement of LEDs having the same peak wavelength), essentially spread all over the visible part of the spectrum. The different radiometric powers for each individual channels are (from blue to red): 0.59, 0.59, 0.41, 0.38, 0.52, 0.32, 1.97, 1.66, 0.31, and 0.34 W. The system can deliver either white light or any light spectrum obtained from the modulation of each of its different wavelength channels. No warm up time is required, and light can be dimmed from 0% to 100% for each channel with a resolution depth of 12 bits (4096 steps).

The design has some limitations, mostly because some components were oversized to make sure it would properly work in terms of thermal dissipation and optical mixing regardless of the price. In addition, since it was the first light engine, the materials were chosen to avoid the expensive initial tooling investment, which would obviously conditioned the final design, preventing us from using injected plastic parts or formed metal parts. The design was not industrially optimized and the rather large number of different mechanical parts makes the assembly process slow and complex. However, this issues only affect the production cost of the device and do not compromise its optical qualities.

On the contrary, because of these initial restrictions and an overprotected design, the SPECTRA TUNE LAB is a light engine with a very good thermal management and optical mixing properties and is the most versatile LED light engine developed with 10 different channels (with the option to extend it to 12 on demand). Therefore, these properties make the SPECTRA TUNE LAB a good candidate for a scientific and research-oriented market, that is not cost-driven but quality-driven.

Recently, several ultra compact spectrometers are appearing in the marketplace, making them suitable as feedback sensors for multi-channel LED light engines that require accurate spectral compensation. In the SPECTRA TUNE LAB, a low-cost miniature spectrometer is included within the tunable LED light source and collects a small fraction of the emitted light after being mixed by the diffuser. This compact spectrometer consists of an entrance slit, a nanoimprinted grating to disperse the light, and a CMOS image sensor. The light is collected from the diffuser element where all the wavelength channels are mixed and are guided with a polycarbonate waveguide (with a flat transmission response in the visible range) to the entrance slit of the spectrometer. Since the light is gathered from the diffuser, we obtain a perfect colour mixing that represents the mixing at the far field. The onboard spectrometer is used as the sensing element for the feedback control system that we will see later on.

The maximum radiometric power that the light engine can deliver is 12.7 W (all channels at maximum power), equivalent to a luminous flux of 3360 lm and an input electrical power of 80 W. However, calculating the luminous efficacy of the source (luminous flux vs electric power) based on this setting is unrealistic, since all channels at maximum power is not a useful SPD and the luminous efficacy ultimately depends on the SPD used [59]. Thus, the efficacy of this light engine can reach values up to 55 lm/W for a CCT of 4000K.

Finally, the SPECTRA TUNE LAB comes with a carrying suitcase and has mounting accessories compatible with standard optical tables and $\frac{1}{4}$ thread for tripod mounting. A C-mount adaptor is included in the set that allows to connect standard compatible light guide connectors in front of the diffuser.

It also comes with a Windows and Mac software, called μWAVE, that has a set of basic operations. In addition, it has a RESTful API available underneath with the whole set of functions and controls accessible with any programming language.

2.1.2 The VEGA 07: a light engine to disrupt the general lighting mass market

From the beginning it was clear that if the aim was to penetrate into a more general lighting market and to be able to install our light engines in hospitals, offices or museums, several important changes had to be done to our early prototypes: cost reduction, size reduction and ease of assembly. These changes were designed to facilitate the transition from a more "craftsman" device to a fully industrial device.

The initial manufacturing cost was too high to succeed in a general market, specially in the lighting market that is very competitive. Therefore, several strategies were adopted, specially in the electronics side, where the cost could be significantly reduced as there are several components that exceeded requirements, or components that could be replaced with similar ones at a lower cost with the same functionality. Furthermore, making a higher investment in tooling, the mechanics cost could also be reduced significantly for large productions.

As it can be seen in more detail in Appendix C, in the VEGA 07 development we merged the two different PCBs that the previous prototypes had, in only one. The LEDs and the drivers are now on the bottom PCB reducing the number of PCBs to a total of two. This also implies fewer connectors which are very costly. On the mechanics side, we have now moved to an injection molding enclosure instead of machined aluminum, and we have reduced the number of parts significantly. And because at first we had several thermal problems, now the LEDs are attached to the back of the module to allow for a better optical mixing and thermal management.

The polycarbonate light guide is very delicate, very easy to get dirty, and slightly overpriced. Thus, during assembly it needs to be handled very carefully so the light transmittance is not affected. On the new design for the VEGA 07, the light guide has been removed and we have designed a new method to lead the mixed light to the colour sensor: guiding it through air with the plastic enclosure itself and making it bounce on an inclined plane to enter the light sensor right underneath.

All in all, the VEGA 07 is a smaller and more compact device, with 7 different coloured LED channels instead of 10, and with a colour sensor inside instead of the spectrometer. It is composed of 48 commercial monochromatic LEDs (from Lumileds Luxeon C [57]: Red, PC Amber, Lime, Green, Cyan, Blue and Royal Blue). The different radiometric powers for each individual channels are (from red to blue): 0.95 W, 2.53 W, 2.2 W, 0.64 W, 1.18 W, 1.08 W and 1.26 W. The number of channels has been reduced, as this will result in a fewer number of drivers allowing for a size reduction, but it will still provide enough spectral resolution for the big majority of applications in human centric lighting applications.

Embedded in the VEGA 07 module are the driver electronics for precise control of current, PWM and light output control, as well as the colour sensor. A close-loop feedback controller allows for colour matching with a target value and provides stability to avoid drifts in time due to thermal or ageing effects. The installation of a colour sensor instead of a spectrometer has some advantages: it is two orders of magnitude cheaper, can withstand higher temperatures, and it is smaller in size. However, it is not trivial to perform a spectral close-loop feedback in a spectrally tunable light engine with only a colour sensor (that only has colour information, not spectral), and we will see later on how this is done.

The maximum radiometric power that the light engine can deliver is 9.7 W (all channels at maximum power), and this is equivalent to 2800 lm and an input electrical power of 80W. However, the efficacy can reach values up to 60 lm/W for a CCT of 4000K.

Besides these differences and others, both light engines share elements. For example, the microcontroller. It handles the PWM signals, the communications, the sensor acquisition system and includes all the intelligence: the algorithms developed to match a target spectrum and the feedback control unit.

2.2 Algorithms to match a target spectrum

In both light engines, the microcontroller's communication driver accepts two methods to produce the desired spectrum associated with two different messages: receiving a full target spectrum, or directly receiving the channel PWM values to be set. When the first method is selected, the control system in the microcontroller calculates the PWM values that produce the best possible match to the target spectrum. When the second method is selected, the PWM weights are calculated beforehand on the PC and then sent to the control unit. The minimum lag time between consecutive spectral updates is 6 ms. The criteria for selecting the first or the second method eventually depends on the application itself.

To perform such fitting to any given target spectrum, we conducted an extensive study on heuristic algorithms (see chapter 4). These algorithms require fast computational times and precise identification of optimal solutions. We investigated three algorithms to perform this optimisation: a genetic algorithm, a Monte Carlo simulation and a simulated annealing. The methods developed are aimed to be implemented in the firmware of the light engine, as well as in the external software.

All three algorithms are based on heuristic methods: techniques to solve problems quickly when classical methods (that seek to find an exact solution) are too slow. For instance, genetic algorithms are adaptive methods that can be used to solve optimisation and search problems. This method mimics the cross-combination of species in nature to improve adaptation to the environment and the survival chances for a species. On a genetic level, the problem is about finding the specific parameters, or chromosomal changes, that help the species to adapt and survive in hostile environments. Because of natural selection, those that are better prepared have higher chances of having more natural descendants and, therefore, of passing on this 'good' adaptation from generation to generation.

On the other hand, a simulated annealing algorithm emulates the crystallisation process in a solid, where atoms are sorted and structured until the lowest level of energy is reached. The transition from one state to the other is achieved by introducing noise in the solutions. This is also a heuristic method because the solutions are based on random numbers. In a Monte Carlo simulation, the process is similar: it operates by creating iterative random solutions that produce progressively better approximations to the final solution with each successive iteration .

All in all, the three algorithms produced comparable results in terms of spectral fidelity (MAPD). However, the genetic algorithm was the most computationally demanding one, whereas the simulated annealing was the fastest - by a factor of 7. This implies that the simulated annealing algorithm corrects the SPD at refresh rates of around >10 Hz, which assures perfectly smooth real-time correction. In contrast, the genetic and Monte Carlo algorithms operate at rates of 1 to 2 Hz, which causes a undesirable visible glitch for the final user, making them unsuitable for real-life situations.

In all cases, it could be seen that the newly generated colour coordinates were very close to the target ones, with the difference in colour being $\Delta u'v' < 5 \times 10^{-4}$.

Although theoretically the solutions achieved were satisfactory, this is an open-loop solution because it does not yet incorporate any feedback sensor. We measured the SPDs of the different channels and set them as the factory defaults or presets, and further assumed that they are immutable over temperature changes and time. All the calculations related to spectral or colour matching were based on the assumption that the presets are correct.

However, this assumption is not true and a corresponding correction is necessary. One widespread and inevitable problem affecting all LEDs [60] is the issue of spectral shift due to temperature changes or due to the LEDs being worn out. Changes in the temperature of the PN junction and aging of the LEDs always lead to undesired fluctuations in the emitted SPD (that can be visible over short or long time scales depending on whether the cause is temperature or age). These changes imply both depreciation in the luminous flux and wavelength shifts (leading to $\Delta u'v' > 0.010$ and MAPD $> 10\%$). Furthermore, in some cases, the PWM modulation may not follow a perfect linear relationship with power, which may induce further errors in the output spectrum (see chapter 4). All these issues have to be solved if a general lighting mass market is to be tackled, since colour difference or luminous flux depreciation are some of the most easily perceivable evidences of a light source malfunctioning.

To correct such colour differences and spectral shifts, we designed two different types of feedback mechanisms using two different types of light sensors: a spectrometer (for the SPECTRA TUNE LAB light engine) and a colour sensor (for the VEGA 07 light engine).

2.3 Feedback control methods for multi-channel LED light engines

2.3.1 Using an integrated spectrometer as feedback means

The SPECTRA TUNE LAB is light engine with a miniature and low-cost spectrometer embedded inside that collects a small fraction of the light emitted by the device. This spectrometer is used as a sensor in a closed-loop feedback controller that is implemented in the firmware of the light engine (see chapter 4).

When active, the implemented feedback mechanism monitors the system evolution and compensates for possible lumen depreciations. Even more importantly, spectral shifts are detected and compensated to ensure a constant SPD over time, despite changes in the LED's overall temperature and efficiency. Hence, the difference between the emitted and target spectra is significantly reduced when a spectrometer is used as a sensor (see chapter 4).

The controller is based on a proportional–integral–derivative controller (PID) implemented independently for each channel. Because it is built on-board, there is minimal lag between signals, processing times are negligible, and the steady state is achieved after a few milliseconds and is thereafter sustained.

The local and immediate effect of the junction temperature can be corrected by monitoring the emitted light. We observed that the relative error increases as the power decreases, which suggests that the input PWM signal (from 0 to 4095) deviates slightly from an exactly linear relationship with the output optical power. However, this nonlinearity can be corrected when the feedback control is active, and both the MAPD and $\Delta u'v'$ are significantly reduced (always leading to about 10% MAPD and $\Delta u'v' < 0.0025$).

The spectrometer-based feedback control effectively corrects all these deviations, preserving the target spectral shape for all output powers despite variations in temperature, aging, and the presence of nonlinearities.

In addition, the method developed is not dependent on the target SPD selected, and can be applied to arbitrary spectra. The method presented also works for different implementations of the light engine. For example by using more LED channels, and can be also used to correct the emitted SPD if a small number of the LEDs break down .

2.3.2 Using a colour sensor as feedback means

The VEGA 07 is a light engine with a colour sensor embedded inside, collecting a small fraction of the emitted light (see Chapter 5 and Appendix C). Colour sensors are two orders of magnitude cheaper than spectrometers, can withstand higher temperatures and are smaller in size; thus, they can be afforded by the general lighting market and create an impact.

However, using a colour sensor as a feedback means in spectrally tunable light engines seems counterintuitive because the function that relates the SPD with colour is not bijective: every SPD has a well-defined colour point, but a given colour point cannot be associated to a single parent SPD, and as a matter of fact, there are an infinite number of SPDs which give rise to the same colour point, because it is a continuous space.

Thus, developing a spectral feedback system using only a colour sensor seems not possible. However, we developed a method that operates by narrowing down the spectral space to a small subset of possibilities, so that it becomes possible to find a positive correlation between colour and spectral accuracy. Our method starts with the known SPD of each LED channel and the target spectrum (and the associated colour point). Using these functions, we can use the heuristic algorithms mentioned in the last section to find the best fit for the target spectrum.

This fit would be perfect with respect to colour and spectral shape if temperature drifts were absent. However, we know that this is not true. Therefore, in our method, the PWM weights of the channels are first adjusted to minimise the spectral difference with the target spectrum (using the developed algorithms) and are then adjusted in a closed-loop to minimise colour deviations from the target colour. In other words, we are prioritising colour accuracy (closed-loop) over spectral fidelity (open-loop). This is a good strategy for the market of general lighting since colour reproducibility is a critical feature as it is the most easily perceivable evidence of a light source malfunctioning. The cooperative relationship between colour and spectral shape makes itself evident when we have a decent initial guess for the spectral solution (i.e. a decent fitting algorithm). For this reason, even if the spectral solution is not optimised directly in a closed-loop as with the spectrometer feedback procedure (see chapter 4), the colour-based closed-loop is sufficient for preserving the spectral shape with an acceptable accuracy (see chapter 5).

After each iteration, the colour of the emitted light is compared to the target colour, and a decision-making block determines the optimal modifications that need to be made to the PWM weights to minimise the difference.

When the feedback control is activated, it effectively corrects this colour deviation, resulting in a $\Delta u'v' < 0.002$ at all times, which is significantly lower than the standard limit established by the lighting industry [3]. Simultaneously, the SPD shape evolves to meet the colour condition, applying slightly more power at some wavelengths and slightly less in others. The error incurred in the target SPD is as low as 10%, as measured by the MAPD percentage.

The method developed is not dependent on the selected target SPD or colour point, and our results are general and can be applied to any desired target spectrum. For all the different CCTs across the Planckian locus, the colour points are kept within 2-step MacAdam ellipses. Moreover, the methods presented also hold for different implementations of the spectrally tunable lighting system. The method was submitted as a worldwide patent application (see appendix A).

2.4 Applications

For decades, artificial light sources have had a static SPD, and their main function has been merely to illuminate objects and spaces. However, today, spectrally tunable light engines have enabled a new set of applications hitherto impossible by manipulating new properties. This development is considered additionally valuable by lighting designers, neuroscientists and medical professionals. Thus, in this project, our light engines were tested and validated at various companies and in different sectors: for example, in hospitals, in offices, and in 24/7 control rooms.

This new spectral flexibility allows us to design SPD optimisation with respect to different parameters or applications. Some of the parameters that can be optimised are listed in chapter 7: flux, efficiency, CRI Ra, TM30-15-Rg, CS, melanopic lux, damage potential and many more.

Through optimisation, different SPDs can be quickly generated with the exact colour coordinates but with a higher fidelity (maximising Rf), with higher saturation (maximising Rg), with lower saturation (minimising Rg) or with a high circadian stimulus (high CS) for human-centric lighting applications.

This is a completely new paradigm for artificial light sources: while the same visual colours or CCT are achieved, different properties are present beneath the surface. For the sake of illustration, in chapter 7, different spectra with the same colour are generated using the SPECTRA TUNE LAB. In all the cases, the colour coordinates are exactly the same, and therefore, their CCTs are also identical: 4000 K. However, the spectral shape is different in each cases and this is the result of optimisation with respect to different parameters: when optimising for maximum CRI Ra, we can reach values as high as CRI Ra = 98.94; when optimising for maximum CS, we can reach CS = 0.45 (with the CRI Ra dropping to 93); when optimising for maximum TM30-15-Rf, the fidelity index reaches Rf = 97.98; and when optimising for maximum TM30-15-Rg, the saturation index is Rg = 105.25 (with the Rf dropping to 66). This illustrates how flexible this technology is.

In addition, these different light settings can be static or dynamic. In chapter 6, we present an experiment performed in ARUP's offices to investigate the effects of these light engines during daytime work hours in an office setting.

The article (see chapter 6) elaborates on the aims and methodology of the experiment that was conducted over a period of 9 weeks in London, United Kingdom. Different lighting conditions were used to test whether the dynamic custom-designed SPDs induced benefits in participants' sleep patterns, alertness, mental effort and mood. The final results are still being analysed and will be published soon.

It is interesting to note that we were able to design dynamic lighting sequences optimised with respect to different parameters, and test them in a real office setting, without interfering with the employees' daily tasks or usual work-load. Moreover, at all times, the spectral transitions were smooth and the changes were perceived as natural.

High melanopic lux in the morning is considered to lead to better attention and higher arousal, while low melanopic lux in the evening is suitable for relaxation and for better sleep at night. In the experiment, one light sequence was designed to vary from cool CCT in the morning to warm CCT in the afternoon, and change its photopic and melanopic lux values from high values in the morning to low values in the afternoon. Another sequence was designed with the same visual parameters as the baseline fluorescent lamps that were previously being using (same CCT and same photopic lux), but with varying melanopic lux values during the day. By comparing this sequence with the baseline, the effects of varying melanopic lux were ascertained by keeping the other parameters constant. With the first sequence, we were able to test not only the melanopic lux effect, but also the effect of concomitant changes in CCT, as the visual comfort and overall experience that the light fixtures evoke is also important for well-being.

Finally, during the last two weeks of the experiment, we developed and tested a new set-up aimed to bring real changes in daylight, as measured outdoors, into the office itself.

We installed a spectrometer on the roof of the office building to measure daylight spectra once every twenty seconds and send the information to the spectrally tunable light engines located inside the office. With the help of a dedicated cloud infrastructure and the heuristic algorithms developed, the fixtures were able to generate a close spectral match to visible daylight and mimic its changing patterns in real-time. The installation was tested over a period of two weeks by 15 workers, who, unaware of the set-up installed and anonymously, commented on their direct observations. They had previously been exposed to only fluorescent lamps for two weeks. Their comments and impressions indicated that mimicking daylight improves the overall subjective experience. More details on this installation can be found in appendix D.

Another installation was carried out in the REPSOL's refinery control room in the city of Tarragona (see chapter 9). There, several luminaires were mounted on the ceiling of a 24/7 working room with 18 employees. These light engines were programmed to follow another pre-defined light sequence adapted to the work shift schedules depending on the time of the day. The room was operated all day, and there was a new work shift every 8 hours.

More precisely, when the work shift started, the light engines supplied a dawn spectrum (CCT = 3000 K) with low intensity, but they quickly evolved towards a more blue-enriched light with higher intensity (CCT = 5500 K). Within minutes, the spectrum started changing progressively towards a neutral light (CCT = 4500 K). After some time, the lighting systems started decreasing the intensity and the blue content to support relaxation. When it was time for the work shift to end, the lighting sequence emulated a full sunset (CCT = 3000 K). Again, at all times, the spectral transitions were smooth and the changes were perceived as natural.

Another installation in a 24/7 control room was carried out in the refinery and oil company ILBOC, in the city of Cartagena. Similar to REPSOL, the room was operated all day with three work shifts per day and had similar lighting conditions.

Sites of other installations included the Intensive Care Unit (ICU) in Hospital Vall d'Hebron in Barcelona and in the Hospital Clínic, also in the city of Barcelona. In both cases, the dynamic sequence designed oscillated between a spectrum corresponding to a CCT of 1850K (evening - low melanopic lux) and that corresponding to a CCT of 6000K (midday - high melanopic lux) to emulate the variation in sunlight over the course of a day. Luminous flux was also varied, with its highest intensity coinciding with the highest CCT or the central hours of the day, as is the case with natural daylight.

ICUs are usually windowless rooms where patients, often intermittently unconscious, have to tolerate difficult conditions for long periods without knowing the time of the day. Our dynamic sequences with changing SPDs and melanopic lux values are designed to help improve the comfort of patients for a fast recovery. In addition, the light quality in ICUs has to meet a certain standard, requiring CRI Ra > 95, to favour the observation of the patient independently of the CCT applied at each moment. More details and some pictures of this installation can be found in appendix E.

2.5 Conclusions

1. Two different light engines were developed and they both reached a stable production line after several prototypes and significant research efforts. A lot of trial and error, optical measurements and thermal experiments were required to ascertain the proper design of the light engines. More specifically:

   (a) The SPECTRA TUNE LAB was the first light engine developed and is designed for scientists. It is the more versatile of the two light engines, with 10 different channels and a spectrometer embedded inside.

   (b) The VEGA 07 light engine is an updated industrial version with fewer parts, optimised with respect to cost, and is smaller in size. With 7 different LED channels and a colour sensor embedded inside, it aims to tackle a more general lighting market.

2. Different optimisation algorithms were designed, tested, and implemented in the firmware of the light engines, as well as in the external software. The algorithms are able to find the best match to any target spectrum, given a set of LED channel SPDs. More specifically:

   (a) Three heuristic algorithms were studied: a genetic algorithm, a Monte Carlo simulation, and a simulated annealing algorithm.

   (b) The simulated annealing algorithm was selected and is currently being used in the firmware and the software because it provides excellent results with regard to spectral fidelity and colour quality ($\Delta u'v' < 5x10^{-4}$).

(c) This algorithm calculates and delivers the best fit at refresh rates of around > 10 Hz, which assures a perfectly smooth real-time correction.

(d) Although they perform well with regard to spectral fidelity, the genetic and Monte Carlo algorithms operate at refresh rates of 1 to 2 Hz, which causes an undesirable visible glitch that can be perceived by the final user, making them unsuitable for real-life situations.

3. Two feedback systems were developed for spectrally tunable lighting systems using two different light sensors. More specifically:

(a) We designed and implemented a closed-loop feedback control system with a low-cost miniature spectrometer adapted inside the light engine.

i. The system is able to monitor and correct spectral deviations in the emitted light and to compensate for spectral shifts due to temperature changes or depreciation of the LEDs.

ii. The overall lumen depreciation may be higher than 10% when the feedback is inactive, but when active, it is less than 1%.

iii. The colour point shows a trend toward more bluish colours with a $\Delta u'v' > 0.010$ when the feedback system is inactive because of temperature changes. However, when active, the feedback system can precisely maintain the colour coordinates with an error $\Delta u'v' < 0.002$.

iv. In addition to temperature-based drifts, the relative MAPD error increases as the power decreases, which suggests that the input PWM signal (from 0 to 4095) is not linearly related to the output optical power. With powers below 10%, the error can reach values of MAPD $> 50\%$ if the feedback system is inactive. However, we are able to correct this nonlinearity, with the spectrometer keeping the MAPD % always around 10% or below.

v. The spectrometer feedback controller is currently implemented in the SPECTRA TUNE LAB light engine.

(b) We designed and implemented a closed-loop feedback control system with a colour sensor adapted inside the light engine. More specifically:

i. Although colour is not a good predictor of spectral shape accuracy as it contains less information, we were able to narrow down the spectral space to a small subset of possibilities using the LED channel presets and the previous heuristic algorithms.

ii. Our method involved two main steps: First, we calculated the channel weights that best match a target spectrum at time zero and, second, we monitored the colour point iteratively using a PID algorithm.

iii. We provided the first cost-effective solution that not only assures colour stability over time ($\Delta u'v' < 0.002$ over the product's lifetime) but also achieves spectral accuracy (spectral errors from the target were about 10%).

iv. The colour feedback control was submitted as a priority patent application and is currently implemented in the VEGA 07 light engine.

4. Our spectrally-tunable solutions are increasingly being used for different applications that involve careful engineering of light spectra. Health lighting, offices, museum lighting, graphics arts industry, retail, horticulture, or 24/7 control rooms with strong productivity needs are good examples of market spaces that demand highly accurate spectral solutions that are reliable and stable over time. During this work, we were able to test the developed light engines in real-world scenarios and validate their spectral properties. More specifically:

   (a) Several installations were done with the VEGA 07 light engine and some of those are listed below:

      i. The light engines were installed in ARUP's offices in London, one of the biggest engineering and architectural companies in the world. Over a period of 9 weeks, different lighting conditions were used to test whether dynamically designed custom SPDs benefited participants' sleep patterns, alertness, mental effort and mood. Although the final results will be published soon, we were able to design dynamic sequences optimised with respect to different parameters and test them in a real-office setting without interfering with the employees' daily tasks or usual work-load. The transitions were smooth and the changes were perceived as natural. In addition, we also installed a spectrometer on the roof of the building to measure daylight spectra every few seconds. With the help of a dedicated cloud infrastructure, we were able to transfer that data inside the office and make corresponding smooth changes in SPD and illumination values in real time. The system was tested by workers over a period of two weeks and their comments indicated an improvement in their subjective experience when compared to that under fluorescent lights.

   ii. The light engines were installed in the control room of a REPSOL oil refinery located in the city of Tarragona. The room, operated 24/7, had work shifts every eight hours and the light sequence designed was adapted to each work shift schedule. Another similar installation included the ILBOC 24/7 control room in the city of Cartagena.
   iii. The light engines were also installed in the Intensive Care Unit (ICU) of two hospitals: Hospital Vall d'Hebron and Hospital Clínic, both in the city of Barcelona. The light sequences designed delivered high melanopic lux and cool CCTs in the morning, and it evolved towards a dimmer intensity and warmer CCTs in the evening. The sequence was designed help to improve the comfort of patients for a fast recovery.

(b) Besides general lighting, our light engines have also been used for research. Some of the universities, companies and research centers using the SPECTRA TUNE LAB light engine include:
   i. The Woolcock Institute of Medical Research and the Woolcock Clinic, in Sydney, Australia. They are focused on the prevention and treatment of sleep and respiratory disorders, lung cancer, and tuberculosis.
   ii. The Newcastle University's Institute of Neuroscience, in Newcastle upon Tyne, United Kigdom. Our light engines are used to study the interaction between light and the brain, as well as how do we understand and perceive colours.
   iii. The University of Oxford, in Oxford, United Kingdom. They use our technology to study the effects of light on the synchronization of circadian rhythms.
   iv. Inserm, the French National Institute of Health and Medical Research, in Paris, France. They study sleep patterns and circadian rhythms and the influence of light on those.
   v. The University of California, Davis, in Davis, USA. They are focused on the study of new artificial light sources for illumination.
   vi. The National Gallery, in London, United Kingdom. Our light engines are used to create high-quality illumination for artworks and study how different pigments are perceived under different light conditions.

Chapter 3

List of selected publications

- **Aleix Llenas** and Josep Carreras "Arbitrary spectral matching using multi-LED lighting systems," Optical Engineering 58(3), 035105 (29 March 2019). `https://doi.org/10.1117/1.OE.58.3.035105`

- **Aleix Llenas** and Josep Carreras "A simple yet counterintuitive optical feedback controller for spectrally tunable lighting systems," Optical Engineering 58(7), 075104 (31 July 2019). `https://doi.org/10.1117/1.OE.58.7.075104`

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systems that mimic daylight," Proceedings of CIE 2018 "Topical Conference on Smart Lighting", Taipei (26 – 27 April 2018).
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Chapter 4

First publication

Arbitrary spectral matching using multi-LED lighting systems

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Optical Engineering 58(3), 035105 (March 2019)

Arbitrary spectral matching using multi-LED lighting systems

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Abstract. Spectrally tunable light sources for general lighting have recently attracted much attention as versatile solutions that can be used in humancentric lighting implementations provided with excellent color rendering and increased user perception. However, temperature and age-dependent color shifts and flux variations in the light-emitting diode (LED) emission are nonresolved challenges that need to be overcome in order to be used in final applications. We demonstrate two strategies that can be used to efficiently and precisely generate arbitrary spectral power distributions (SPDs) using multichannel LED engines. First, we introduce different methods to match a given SPD and select an algorithm (simulated annealing) in virtue of its speed (in the milliseconds range) and accuracy (color shifts $\Delta u'v' < 5 \times 10^{-4}$). Then, we propose a closed-loop feedback control (PID) to compensate for spectral shifts due to temperature changes or lumen decay of the LEDs. Both methods can be used independently, but only a combination of them (which uses the output of the first method as an initial guess for the second) offers fast computational times and high spectral accuracy and precision. Computation times are important because these algorithms are intended to be executed on dedicated microprocessors integrated in the LED modules, often sharing scarce memory and processing resources. The results presented here are aimed to be universal and hold for different implementations of the light engine and any number of LED channels. [DOI: 10.1117/1.OE.58.3.035105]

Keywords: solid-state lighting; light-emitting diodes; color; feedback; light; spectrometers.

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1 Introduction

Spectrally tunable light engines are gaining increasing attention after several research efforts have shown how they can be used to create dynamic spaces and mimic daylight patterns with respect to human circadian rhythms and physiology.[1,2] Solid-state lighting (SSL) is now a mature technology that is fully compatible with current digital systems and information technology. Light-emitting diodes (LEDs) are today present in a wide range of wavelengths across the visible and IR regions, showing fast time responses (in the microsecond range). In addition, LED presents narrow emission bands (typically about 20 nm), low power consumption, long lifetimes, and good dimming capabilities.[3]

Currently, the role that light plays in the regulation of our approximately 24-h circadian rhythm is well accepted and understood.[4,5] It also affects our body temperature,[6] attention,[7] hormonal secretion,[8] and sleep.[9] The discovery of a fourth type of retinal photoreceptor, the intrinsically photosensitive retinal ganglion cells (ipRGCs), in the 1990s was the missing link proving that light not only plays an image forming role but also has an equally important non-visual influence on our sleep-wake cycle.[10] ipRGCs are sensitive to light in a particular wavelength range, peaking at around 480 nm (melanopic region).[10] This explains why not only illuminance levels or colorimetric properties such as the correlated color temperature (CCT) or color rendering index[11] of light are important, but the whole spectral information of light, i.e., the spectral power distribution (SPD), needs to be considered. Because of these recent discoveries and due to the timely incursion of spectrally tunable solutions in an increasing number of color applications[12–15] and humancentric lighting (HCL) applications,[16–19] the benefits of multichannel LED light engines are now accepted for residential, business, public health, commercial, and industrial sectors.

In the literature, several LED multichannel systems can be found for different applications. Park et al.[20] used an LED array system for a multispectral camera. Fryc and Brown[21] proposed a light engine to match CIE standard illuminants, Kolberg et al.[22] developed an LED solar simulator with the ability to modulate certain wavelengths, Tan et al.[23] implemented a wireless control for lighting systems that demonstrated high energy savings, and Burgos et al.[24] developed a spectral LED-based tunable light source. Although some of these works achieve at first good quality results after long computational times, none of the proposed methods take into account spectral shifts due to temperature changes or wear out of the LEDs (a widespread and inevitable problem that affects all LEDs[25]), and none of them includes a feedback control system to monitor the emitted light, a key issue if a high quality and long lasting light source is pursued. In the line of the present work, Chew et al.[26] developed a spectrally tunable lighting system with eight channels and a closed-loop control. The algorithm developed by these authors proved to be also slow (more than 80 s for stabilization) and with a poor spectral fidelity (color difference within a five-step MacAdam ellipses[27]), which limits its applicability in practical scenarios.

The aim of this work is to provide new control methods that offer both high spectral fidelity and short computational processing times. The first obstacle to surmount is the fact

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that the output spectrum in the devised applications is not static (i.e., for HCL applications the spectrum changes over the course of the day). Since time-dependent signals applied to the LEDs bring about a distribution of different junction temperatures (therefore causing spectral shifts and optical power variations), the problem of predicting the spectral output through heat transfer equations (compact modeling) becomes unmanageable. The inaccuracy of some of the parameters (junction thermal resistance as a function of temperature, thermal capacitance, emissivity of different materials, convection coefficients, etc.) is high, and the problem is far from equilibrium because the spectrum is continuously changing over time. Thus, a new sensor feedback approach borrowed from control theory has been adopted.

We have divided this study into two sections. The first section is devoted to the calculation of the pulse-width modulation (PWM) weights that best match a target spectrum by means of heuristic algorithms, never used in this field before. Results obtained by a genetic algorithm, a simulated annealing algorithm, and a Monte Carlo simulation have been tested and analyzed for the case under study. Once the PWM weights for the target spectrum have been calculated, a second section shows how a proportional integral-derivative controller system (PID) can be used to finely tune the PWM weights and compensate for small spectral changes in the LEDs, primarily caused by thermal junction variations or by the nonlinear response of the LEDs. The proposed algorithm can also be used to compensate for aging of the LEDs or even failure of a small number of LEDs.

2 Methodology and Results

2.1 *What Is the Most (Time) Efficient Algorithm to Match a Target Spectrum by Using Combinations of LED Spectra Having Different Peak Wavelengths?*

The tunable light source developed in this work has 48 commercial monochromatic LEDs (from Lumileds Luxeon C:[28] Deep Red, Red, Amber, PC Amber, Lime, Green, Cyan, Blue and Royal Blue; and from Lumileds Luxeon Z UV:[29] 425–430) arranged in 10 individual channels (a channel should be regarded as an arrangement of LEDs having the same peak wavelength), essentially spread all over the visible part of the visible spectrum (400 to 700 nm, see Fig. 1). The different radiometric powers for each individual channels are (from blue to red): 0.59, 0.59, 0.41, 0.38, 0.52, 0.32, 1.97, 1.66, 0.31, and 0.34 W.

A block diagram of the hardware can be found in Fig. 2. The control system is executed in a microcontroller in the light engine. The same microcontroller also handles the PWM signals, the communications, and the sensor acquisition system, which include readings from the power sensors, the temperature sensors, and the spectrometer. The PWM constant current driver has a resolution depth of 12 bit. The overall system is controlled with a Python 3.4 program and a PC (Intel i5, 8 GB RAM) through a serial communications system RS-485.

The communication driver accepts two methods to produce a desired spectrum associated to two different messages: (a) receiving a full target spectrum (81 two-dimensional float data points with wavelengths and radiant flux values) or (b) directly the channel PWM values to be set (10 integer values from 0 to 4095). When the first method is selected, the control system calculates the PWMs values that give rise to the best possible fit to the target spectrum. When the second method is selected, the PWM weights are previously calculated in the PC and then sent to the control unit. The minimum time between consecutive spectral update is 6 ms. The criteria for selecting the first or the second method eventually depend on whether an external server is available to perform the calculations for the application under consideration.

Once a target spectrum $S^t(\lambda)$ is set, fast optimization algorithms are required to efficiently find an optimal solution. An arbitrary spectrum can be represented by $S(\lambda) = \sum_{n=1}^{10} A_i L_i(\lambda)$, where $L_i(\lambda)$ and A_i are the spectral flux (W/nm) and weighting amplitude of the i'th channel, respectively.

The error function used to estimate the spectral fidelity is the mean absolute percentage deviation (MAPD), measured for each wavelength j, and defined by Eq. (1) for a system of K wavelength points (in our system K is a linear array of 81 points, representing the wavelength range between 380 and 780 nm, in 5 nm steps):

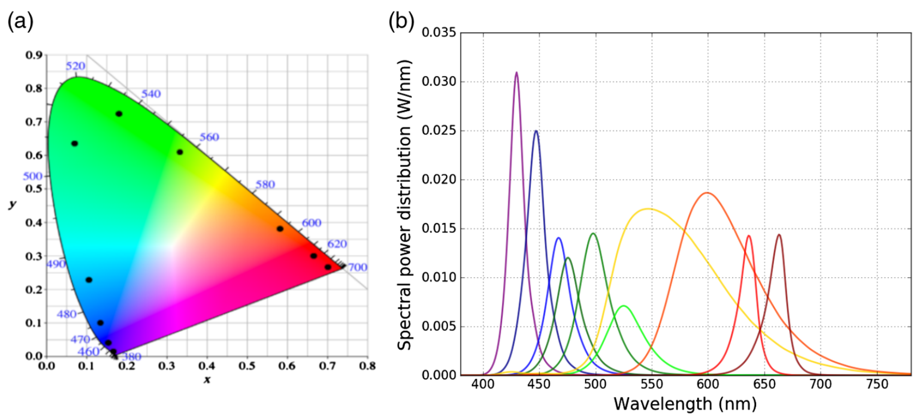

Fig. 1 (a) CIE 1931 xy coordinates of the 10 channels that define the color gamut and (b) the SPD of the 10 LED channels.

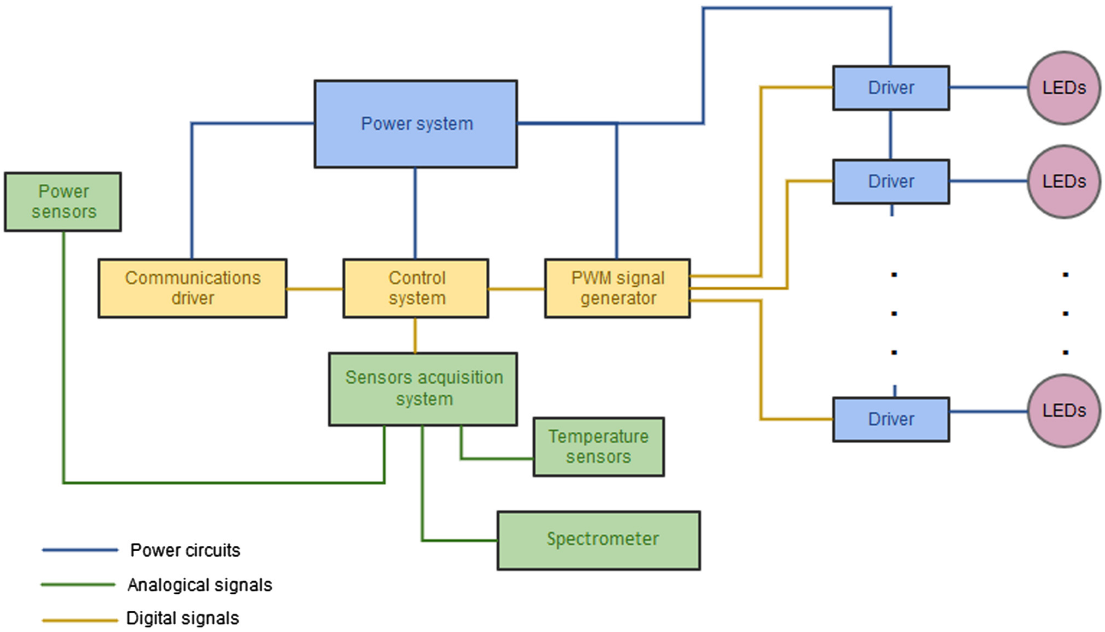

Fig. 2 Light engine hardware block diagram.

$$\mathrm{MAPD} = \frac{100}{K}\sum_{j=0}^{K}\left|\frac{S_j - S_j^t}{S_j^t}\right|. \tag{1}$$

We have investigated three different heuristic approaches: (i) a genetic algorithm, (ii) a simulated annealing, and (iii) a Monte Carlo simulation. In all cases, the input parameter is the target spectrum to be matched, the known variables are the full set of LED channels' SPD, and the unknown variables are the PWM weights that best fit the target spectrum, as dictated by the MAPD. The PWM weights are free variables that can be varied only in the range from 0 to 4095 (PWM has a 12-bit resolution). The algorithms were designed to stop when the situation was such that further iterations were not contributing to improve the MAPD result from previous iterations (convergence criteria). Succinctly, the results presented in this first part deal with MAPD minimization while keeping short computation times.

2.1.1 *Genetic algorithm*

A genetic algorithm is a method inspired by natural selection principles that can be effectively used in optimization problems. This method includes concepts emerged from the well-known theory of evolution such as inheritance, mutation, selection, and crossover. Starting from a population of individual solutions (initial guess), the algorithm continuously modifies them and creates new solutions by crossing two of them together and applying random mutations. After several new generations, the system tends to evolve toward an optimal global solution, as supposedly biological species have done.

The basic workflow of our genetic algorithm is as follows:

1. Starting from a population of randomly generated solutions (called chromosomes), the error to the target is measured, and the best solutions are chosen and set apart.
2. New solutions are generated by combining (crossing) the previously selected solutions in pairs of two.
3. Randomly, a selected number of them are mutated to avoid falling into local minima.
4. Start over from step 2 until convergence to the desired solution is obtained.

2.1.2 *Simulated annealing algorithm*

The simulated annealing was invented to generate sample states of thermodynamic systems. Given a random solution, it is slightly perturbed by adding or subtracting small amounts, and the error to the target solution is calculated. In case, the new solution improves the error of the previous iteration, the new weights are updated and the process continues over a loop. As the number of iterations increases, the strength of the perturbation is decreased to warrant a fast convergence to a solution. This algorithm handles local minima by giving a likelihood of accepting a solution even when it increases the error as compared to the preceding iteration.

The main steps of a simulated annealing algorithm are:

1. An array of random coefficients is generated and the error is calculated.
2. Perturbation of the currently accepted solution: a small random amount is added or subtracted to the initial array (in subsequent iterations the perturbation gets reduced).
3. The new error is calculated.

a. If error is lower or equal than in previous iteration: change gets accepted.
b. If error is higher than in previous operation. Either
   i. it gets accepted with a small probability (avoid local minima).
   ii. it is refused with a high probability.

4. Start over from step 2.

2.1.3 *Monte Carlo algorithm*

Monte Carlo methods are widely used in many branches of science. In our case study, an initial guess to the solution is multiplied by an array of random numbers, for which the magnitude is decreased in successive iterations until reaching convergence. For each iteration, the algorithm passes the best solution (lowest error) over to the next iteration to keep on refining the optimization process.

For a Monte Carlo simulation, the main steps are:

1. The initial guess is set to an array of 10 components with value 4095 (all LED channels set to full power).
2. An array with random numbers is generated (the magnitude of these numbers is decreased with increasing iterations). Afterward, the array is multiplied by the currently accepted solution array (weighting amplitudes).
3. The error is calculated for each array resulting from this multiplication, and the one with the lowest error is passed to the next iteration.
4. Start over from step 2.

2.1.4 *Computational time results*

Table 1 shows the results obtained with the three different heuristic algorithms under study. In all cases, we used as target SPD: a D65 illuminant (CIE Daylight of CCT $\simeq$ 6500K)[30] because it is the standard accepted representation of natural daylight; an incandescent SPD as the most traditional lighting technologies (CCT = 2636K); a white LED SPD as one of the latest lighting technologies (CCT = 6464K); and the melanopic SPD, because ipRGCs are sensitive to this light spectrum and this is the mechanism that regulates our 24 h circadian clock. The outcomes relevant for our study are the MAPD to assess the spectral fidelity [Eq. (1)] and the computational time, defined as the time elapsed during the calculation of the PWM weights.

Table 1 Heuristic methods comparison: a genetic algorithm, a Monte Carlo simulation, and a simulated annealing.

Target spectrum	Parameters	Genetic	Monte Carlo	Simulated annealing
Daylight D65	Computational time (s)	0.667	0.340	0.085
	MAPD	10.1	10.3	10.4
Incandescent	Computational time (s)	0.667	0.335	0.093
	MAPD	14.3	14.3	14.1
Melanopic	Computational time (s)	0.650	0.320	0.093
	MAPD	8.2	8.1	8.3
White LED	Computational time (s)	0.667	0.340	0.086
	MAPD	5.9	5.5	6.1

The three algorithms give comparable results in terms of spectral fidelity (MAPD), as can be seen in Table 1. However, the genetic algorithm was the most computationally intense while the simulated annealing was the fastest, by a factor of 7. This implies that the simulated annealing algorithm corrects the SPD at refresh rates of around >10 Hz, which assures a perfectly smooth real-time correction that is not perceptible to the naked eye. In contrast, the genetic and Monte Carlo algorithms operate at 1 to 2 Hz, which causes a nondesired visible glitch that can be perceived by the final user, making them unsuitable for real-life situations.

Figure 3 shows the SPD of the light engine for each target spectrum generated with the coefficients given by the simulated annealing algorithm (similar results are obtained with the other algorithms). The color difference was measured using the CIE 1976 L^*, u^*, v^* (CIELUV) color space (u', v')[31] since it is a well-accepted metric for assessing the chromaticity of SSL products,[32] and results are reported in Table 2. In all cases, it can be seen that the new generated color coordinates are very close to the target ones, being the difference in color $\Delta u'v' < 5 \times 10^{-4}$, which is way below the chromaticity deviation threshold recommended for SSL products.[32]

2.2 *(Computationally) Low-Demanding PID Controller for Accurate Spectral Fidelity Against Thermal Junction Variations and LED Luminous Flux Depreciation*

As a consequence of either changes in the PN junction temperature or aging of the LEDs, the emitted SPD is always submitted to nondesired fluctuations (that can be at short or long time scales depending on whether the originating mechanism is temperature or aging). These changes may imply both depreciation in the luminous flux and/or wavelength shifts. Also, they are generally noticeable to the naked eye and worsen with aging of the LEDs. Furthermore, the PWM modulation may not follow a perfect linear relationship with power, which may induce further errors in the output spectrum, especially at low powers.

The printed circuit board (PCB) temperature increase during 1 h when the light engine is at 80% of its maximum power is exponential: it increases from room temperature (25°C) to 60°C. This is the typical time-scale of the temperature transient until the steady state is reached for this particular light engine, which means that a precise monitoring of the PWM weights must be done at a suitable refresh rate. These relatively fast changes in the temperature affect the overall performance of the system in the same time-scale.

Recently, several ultracompact spectrometers are appearing in the marketplace, making them suitable as feedback sensors for multichannel LED light engines that require accurate spectral compensation. In our prototype, a low-cost miniature spectrometer is included within the tunable LED light source and collects a small fraction of the emitted light

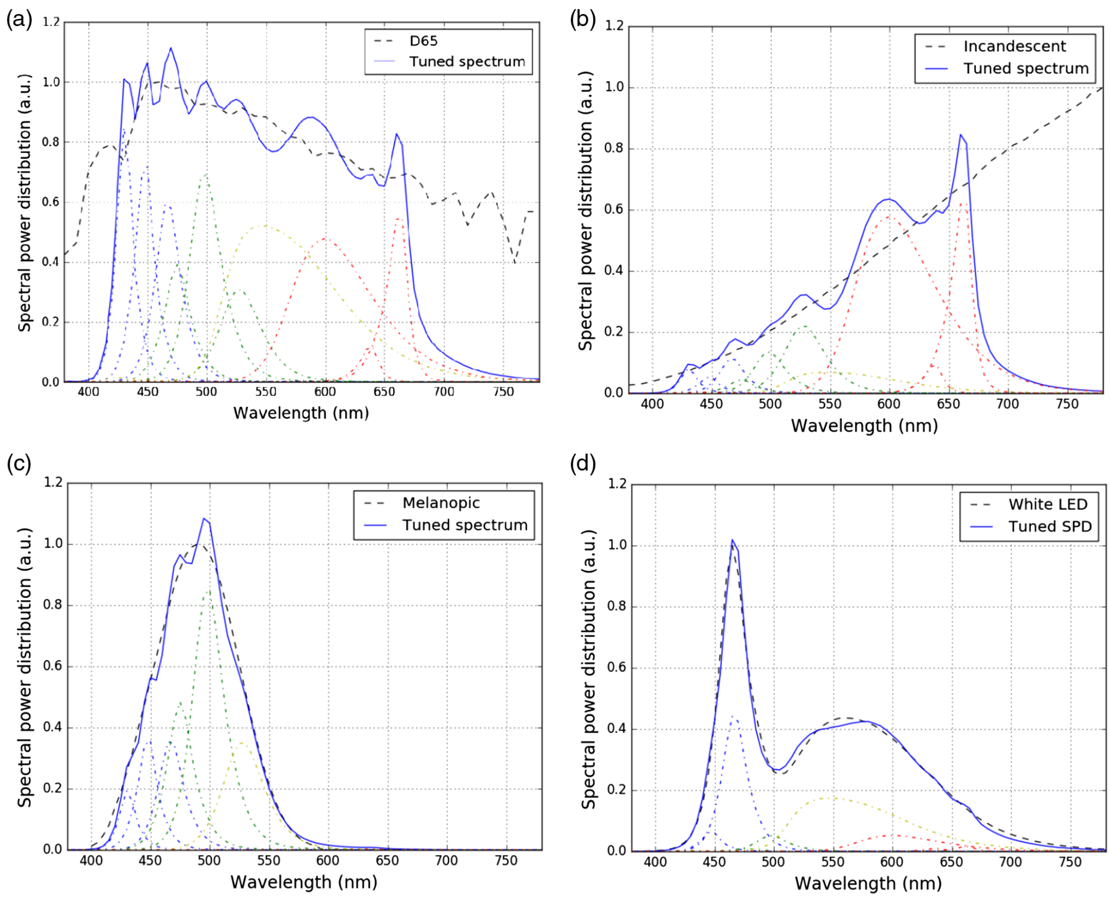

Fig. 3 Truly spectrally tunable light engines can generate arbitrary spectra. These four examples show (a) the best fit (blue solid line) to daylight D65, (b) an incandescent spectrum, (c) the melanopic, and (d) a white LED spectrum (Ph-LED YAG) (dashed black lines) made by optimizing the weights of the 10 different channels of the LED light engine (colored dash-dot lines). In all cases, the spectra were normalized and are shown in arbitrary units.

Table 2 Color coordinates difference ($\Delta u'v'$) between target/tuned SPD.

	Daylight D65	Incandescent	Melanopic	White LED
$\Delta u'v'$	0.0004	0.0005	0.0003	0.0002

after being mixed by the diffuser. This compact spectrometer consists of an entrance slit, a nanoimprinted grating to disperse the light, and a CMOS image sensor. The light is collected from the diffuser element where all the wavelength channels are mixed and are guided with a polycarbonate waveguide (with a flat transmission response in the visible range) to the entrance slit of the spectrometer. Since the light is gathered from the diffuser, we obtain a perfect color mixing that represents the mixing at the far field.

The on-board spectrometer is used as the sensing element for the PID control system. It takes real-time measurements of the color-mixed SPD emitted by the LED channels and detects if the spectral shape, color, and luminous flux have changed from the previous iteration. All the information is passed to the PID controller and new PWM weights for each channel are found until the calculated error is below an acceptable threshold. A schematic of the modeled system is shown in Fig. 4.

Each LED channel is governed by an independent PID control. However, given an SPD obtained with the spectrometer, it is not possible to separate out the contributions of each individual channel since a given spectral region is covered by multiple LED channels as seen in Fig. 1(b), so the system becomes overdetermined. To overcome this limitation, our method compares flux and wavelength shifts only at channel peak wavelengths, which are unique for each channel. This assumes that channels are independent and there is not cross-talk between them at the positions where the channels peak, which has been largely verified.

Each PID controller follows Eq. (2), where $u(t)$ is the signal, $e(t)$ is the current error (defined as the difference between the target and the output signal), k_p is the controller

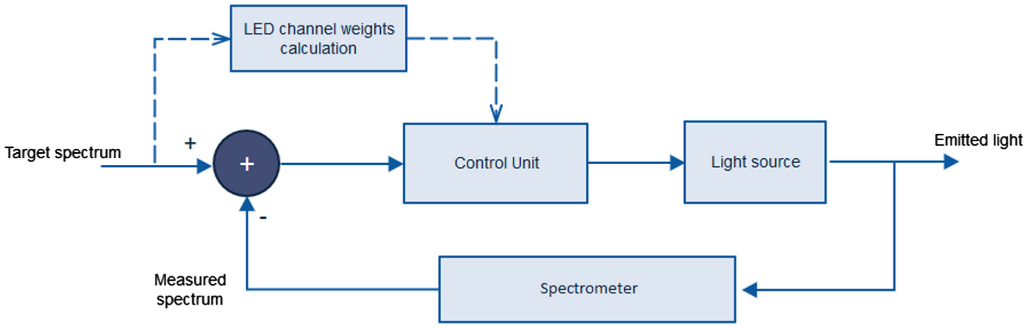

Fig. 4 Schematic of the implemented close-loop feedback system.

path gain, T_i is the integral time constant, and T_d is the derivative time constant:

$$u(t) = k_p e(t) + \frac{k_p}{T_i}\int_0^t e(t)\mathrm{d}t + k_p T_d \frac{\mathrm{d}e(t)}{\mathrm{d}t}. \tag{2}$$

Since we are working with a digital signal, Eq. (3) can be used instead of Eq. (2). The PID has three different proportional, integral, and derivative parameters. The integral part acts on accumulated past errors and the derivative part is a prediction of future errors that depends on the rate of change. The PID parameters are generally found following a trial/error process until a fast convergence with a low overshoot is obtained (in our system this tuning process resulted in values $k_p = 0.5$, $k_i = 0.5$, $k_d = 0.1$):

$$u[n] = k_p e[n] + k_i \sum_{i=0}^{n} e[i] + k_d(e[n] - e[n-1]), \tag{3}$$

where $k_i = k_p/T_i$ and $k_d = k_p T_d$.

2.2.1 *Spectral PID control results*

For the sake of comparison, Fig. 5 shows the time evolution (1 h) of the system with (a) the feedback off and (b) with the feedback on. The efficiency of the LEDs decreases as time goes by and there is also a decrease in flux in all parts of the SPD, which is stronger in the red region. Thus, color coordinates show a trend toward more bluish colors with a $\Delta u'v' = 0.010$, for the same period of time. The overall lumen depreciation may be higher than 10% when the feedback is off. Even if we are in a best case scenario where the spectrum is static and the time window is only 1 h, the observed color shifts and lumen depreciation would never be acceptable by the lighting industry.

When active, the implemented feedback monitors the system evolution and compensates for a possible lumen depreciation. Even more importantly, spectral shifts are detected and compensated to ensure a constant SPD over time despite changes in the overall LEDs temperature and efficiency. Hence, the difference between the emitted and target spectra is significantly reduced.

This behavior shows to be consistent over time: when a decrease in flux is detected, higher power is provided to those channels that maintain the flux constant. In this process, color coordinates may experience minor shifts but still are not visually perceivable ($\Delta u'v' < 2 \times 10^{-3}$). Since the controller is built on-board, there is minimal lag between signals, processing times are negligible, and the steady state is achieved after a few milliseconds and keeps stable after that.

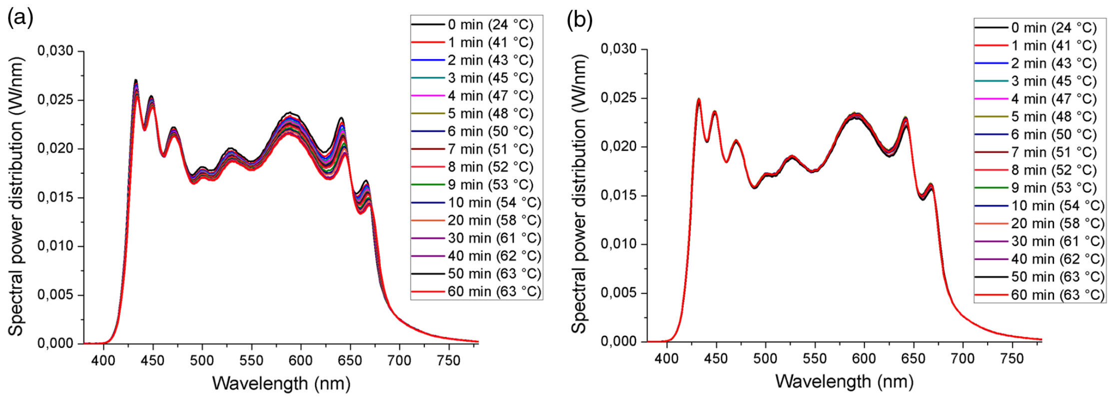

Fig. 5 Emitted spectrum over time when all the LED channels are at 80% of their maximum power with (a) the feedback off and (b) with the feedback on. Temperature in the LEDs PCB is shown (owing to the thermal resistance specified in the LED datasheets and neglecting the welding resistance as a first approximation, the junction temperature is estimated to be 10°C higher than the PCB).

The overall lumen depreciation is less than 1% when the feedback is on.

To validate spectral errors, we have used an external spectrometer (CAS 120 by Instrument Systems). The local and immediate effect of the junction temperature can be corrected by monitoring the emitted light. Figure 6(a) shows the difference between the emitted spectrum and the target spectrum at different output powers. As can be seen, the relative error increases as the power decreases, which suggests that the input PWM signal (from 0 to 4095) is not linear with the output optical power. However, this nonlinearity can be corrected when the feedback control is active as shown (in terms of the MAPD and color differences) in Figs. 6(b) and 7, where the MAPD and $\Delta u'v'$ are significantly reduced. The feedback control effectively corrects all these deviations [see Fig. 6(b)], preserving the target spectral shape for all output powers despite variations on temperature, aging, and presence of nonlinearities. It is worth noting that even with all these effects taking place, not only the spectral shape is kept constant within a small error but also the feedback mechanism preserves also the color point throughout the product lifetime within an absolute error below $\Delta u'v' < 0.0025$, which is way below the limit established by the lighting industry standards.[32]

The method presented here is not dependent on the selected target spectrum and its use and effectiveness hold for any light spectra as well as for different implementations of the device, for example, by using more LED channels or different optimization algorithms to calculate the channel weights.

It is also worth noting that even though our algorithms ensure high precision and accuracy (refer to Tables 1 and 2), this is not a strict requirement for the overall method to work as desired since the spectral matching algorithms provide only an initial guess for the PID, which from this initial estimate uses real spectral measurements to iteratively correct the output. However, because changes in color and/or flux may be perceived during transition times between iterations

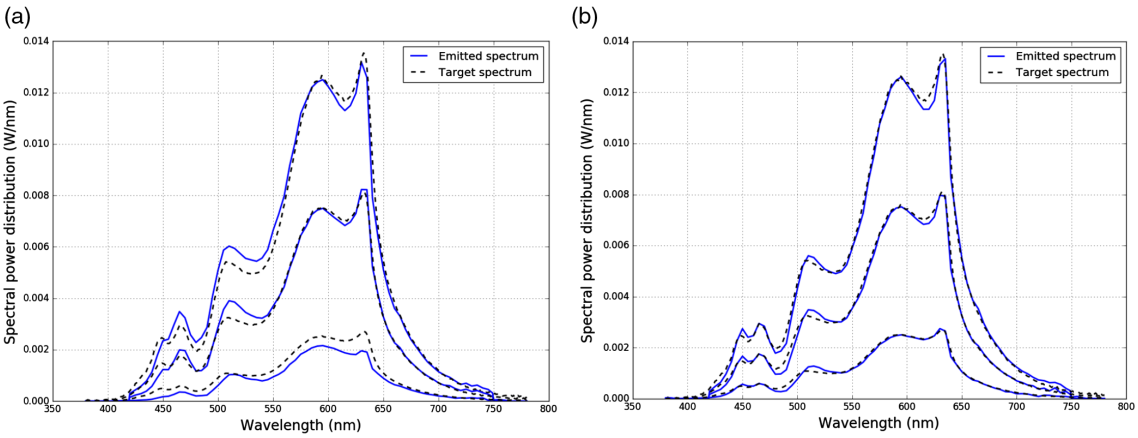

Fig. 6 Comparison between the target and the emitted spectrum for different powers (50%, 30%, and 10%) with feedback functions (a) off and (b) on.

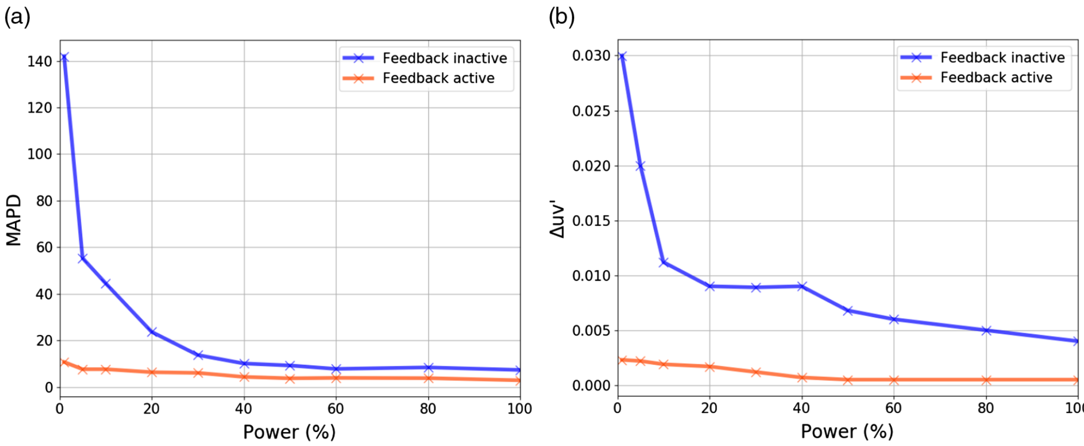

Fig. 7 (a) MAPD and (b) color difference comparison between target and emitted light when feedback is on and off.

(especially if the first guess is far from the optimal result), it is better to begin with a good enough initial estimate to build upon.

3 Conclusions and Future Work

LED engines with added intelligence and spectral awareness offer great possibilities to create healthier living spaces by having a complete control over the full visible spectrum. The methods developed in this work provide tools and offer robustness to SSL tunable light sources that can be used to boost different applications in lighting, automobiles, transportation, communication, imaging, agriculture, or medicine. The methodology presented may be applied to lamps with any number of channels, from a simple red-green-blue, red-greed-blue-amber-white, or more complex 10-channel engines as the ones studied in this work.

We have shown two different methods that may be used to generate arbitrary SPDs using multichannel LED engines. In the first part, we performed an in-depth study of different heuristic algorithms that can be used to find the channel weights that best match a target SPD. Results showed that the simulated annealing algorithm gives excellent results with regards to spectral fidelity while at the same time involving extremely low computation times. In the second part, we implemented a closed-loop control system to monitor and correct spectral deviations in the emitted light and to compensate for spectral shifts due to temperature changes or depreciation of the LEDs. We demonstrated a reliable and robust method that is able to keep an emitted spectrum constant and stable over time.

Many applications (i.e., medicine, agriculture, imaging, and museum lighting, among others) are in need of highly accurate light spectra that do not produce undesired shifts or optical power variations over time. Our methods set a general framework for multichannel SSL systems and the results and conclusions achieved are universal, which means that they can be applied to different systems and lighting technologies.

The methods presented here minimize the MAPD difference to a target spectrum. This approach assumes that as the MAPD decreases so does the color difference $\Delta u'v'$. Even though this holds true for most of the cases, it is out of the scope of this work to provide methods that improve the color difference of the emitted light independently of the spectral shape. Potentially, the color difference could also be controlled with other heuristic algorithms specially designed to minimize the $\Delta u'v'$. As a future work,[33] due to the cost associated with current miniature spectrometers, it will be helpful for the research community to develop an implementation of a joint spectral/color correction algorithm with a new type of CIE 1931 XYZ color sensor (which is much cheaper) embedded in the light engine in substitution of the more costly spectrometer. This would allow our methods to scale up and be directly applicable to the general lighting market, which is so far more cost-driven than technology-driven.

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Chapter 5

Second publication

A simple yet counterintuitive optical feedback controller for spectrally tunable lighting systems

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A simple yet counterintuitive optical feedback controller for spectrally tunable lighting systems

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Abstract. We explore methods that efficiently replicate arbitrary spectra with both high precision and accuracy using multichannel light-emitting diode (LED) lighting systems. It is well known that LED-based light sources deteriorate over time and change their spectral output with varying operating junction temperatures. A simple open-loop approach to the spectral matching problem would bring about unbearable spectral and color inaccuracies. In the literature, different solutions have been studied that make use of integrated spectrometers as closed-loop feedback elements that warrant spectral awareness and self-correction. However, the prohibitive cost of small spectrometers (that generally involve CMOS-based gratings) constitutes a high barrier that prevents their integration into final lighting products. We demonstrate how a cost-effective colorimeter can be used not only to preserve the color point of the target spectrum but also to keep the spectral matching error extremely low (relative spectral error <10%). With the proposed system and methods, we obtain relative color differences between target and emitted spectra below $\Delta u'v' < 0.002$, always with spectral shape preservation. [DOI: 10.1117/1.OE.58.7.075104]

Keywords: solid-state lighting; light-emitting diodes; color; feedback; light.

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1 Introduction

For centuries, humans performed all daily activities under the light of the sun. Its well-defined, dynamic, broadband, and ever-changing spectrum is what we perceive as natural. Today, while the influence of the sun's spectrum in our biology remains unchanged, we have mastered several artificial lighting technologies. This is because our main activities have shifted to happen inside buildings, shortening our daily natural light exposure.

The blueprint for lighting in occupational settings is based on the well-established visual effects of light, with aspects such as illuminance, glare, color-rendering index (CRI), and correlated color temperature (CCT) being considered.[1] Even though provided with all these quality indicators, the main artificial lighting technologies used nowadays are white-light-emitting diodes (LEDs) and fluorescent lights, sources known to have a spectral power distribution (SPD) that substantially differs from natural light.[2,3]

However, today we know that in parallel to the neural pathway that processes visual responses to light (the so-called "visual pathway"), there is also a nonvisual pathway that shapes many cognitive functions in our brains. Currently, the role that light plays in the regulation of our approximate 24-h circadian rhythm is well accepted.[4,5] It also affects our body temperature,[6] attention,[7] hormonal secretion,[8] and sleep.[9] The discovery of a third type of retinal photoreceptor, the intrinsically photosensitive retinal ganglion cells (ipRGCs), in 1990s was the missing link proving that light does not only play an image-forming role but has an equally important nonvisual influence on our sleep-wake cycle. Furthermore, melanopsin is a photopigment found in the ipRGCs of the eye and is the most sensitive to wavelength of ∼480 nm.[10] This explains why not only illuminance levels or colorimetric properties, such as the CCT or CRI, of light are important, but the whole spectral aspect of light, i.e., the SPD, needs to be considered. Spectrally tunable lighting systems are now being used in residential, office, and public health settings, as well as commercial and industrial sectors.[11,12]

The traditional lighting market is struggling today with a redefinition of its very own language, one that incorporates the ever-growing scientific evidence of the influence that dynamic light has on animals and biological species. However, some obstacles need to be overcome before the different parts combine into a mainstream technology. The first obstacle relates to the fact that daylight always implies dynamism. The spectrum of the sun changes over the course of the day, which from a product development perspective means that the varying signals applied to the LEDs lead to a distribution of different junction temperatures. Since LEDs are made of semiconductor materials, they are very sensitive to temperature variations and change their emission peak wavelength and intensity. Not only is the spectral accuracy compromised if temperature effects are not properly accounted for, but also the associated color variations are easily perceived by the naked eye. All these effects need to be corrected in order to end up having a technology that aims at competing with the current standards of the lighting industry.

Multichannel LED light engines are good candidates to satisfy the demand that a shift to a truly spectral lighting would imply. The problem that we are facing here is twofold. (i) How can multichannel LED sources, where every channel has its own temperature dependency and aging mechanisms, guarantee spectral and color stability over their lifetime? (ii) How can this be done without a significant cost increase? Technically speaking, several approaches can be considered as follows.

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i. The simplest approximation involves measuring the SPDs of the different channels as factory defaults or presets and further assumes they are immutable over temperature changes and time. All the calculations related to spectral or color matching algorithms will assume the presets are correct. This is what is called an open-loop method, because it does not incorporate any sensor feedback.
ii. One could also consider using a small spectrometer embedded inside the light engine that monitors and corrects the spectral shape of the emitted light in real time. This would be probably the most logical solution to come with for preventing color and spectral shifts due to temperature changes or wearing out of the LEDs.
iii. Optical feedback with a, i.e., RGB, colorimeter constitutes another possibility if the main aim is to improve color consistency. However, there is no way a strategy based solely on a color sensor can provide an acceptable level of spectral accuracy, since there are an infinite number of spectra that represent the same color point. This would be equivalent to say that color, by itself, is not a good predictor of spectral shape accuracy because it contains less information.
iv. As a final option, several photodiodes or colorimeters could be placed in front of every light channel to account for color or intensity variations. Technically speaking, this would be pretty challenging since there would be cross talk between lights from neighbor channels. This could be theoretically solved through sequential measurements by switching on/off the channels with a frequency not perceivable by humans. However, the complexity of the solution and the concern about the visible flicker renders this approach infeasible.

In the literature, several works based on the first approach (i) can be found. Fryc and Brown[13] proposed a light engine to match CIE standard illuminants, Kolberg et al.[14] developed an LED solar simulator with the ability to modulate certain wavelengths, and Burgos et al.[15] developed a spectral LED-based tunable light source. Although some of these works at first achieve good-quality results, none of the proposed methods takes into account spectral shifts due to temperature changes or wear out of the LEDs (a widespread and inevitable problem that affects all LEDs),[16] and none of them includes a feedback control system to monitor the emitted light, a key issue if a high-quality and long-lasting light source is pursued.

Considering that our main objective is to reliably match a given target spectrum, the obvious choice would be to use a spectrometer to measure the emitted spectrum, and from the SPD calculate the color point, thereby using a combination of (i) and (ii). In a previous work, we already studied such a system involving (i) and (ii) and the results were also published in this journal.[17] The present work can be considered as the natural research evolution of our first paper on this topic, where we have expanded our methods to include a colorimeter instead of a spectrometer as a sensing element, preserving the spectral accuracy to a good extent. It is worth noting that the conclusions of our first work still hold true, and a method based on an embedded spectrometer is still the best approach to attack the spectral consistency problem. Our aim with the present work is to expand our first method to color sensors, which are two orders of magnitude cheaper, and thus can be afforded by the general lighting market and create an impact.

Alternatively, combining (i) and (iv) would also be very similar to our previous work, since using a photodiode or color sensor for each LED channel is, in effective terms, a simplified spectrometer tailored to the particular LED.

Throughout the following sections, we shed light onto the nonobvious gap between the combination of (i) and (iii). Indeed, it may seem a counterintuitive combination due to the fact that the function that relates SPD and color is not bijective, that is, every SPD has a well-defined color point, but a given color point cannot be associated to a single parent SPD, and as a matter of fact, there are an infinite number of SPDs giving rise to the same color point because it is a continuous space. So, if color is not a good spectral predictor, how can it be used to preserve spectral stability?

This question deserves some thought beforehand, since it is important to understand the value of this research not only for the scientific community but also for those aiming to build commercial spectrally tunable solutions that are both reliable and cost-effective.

The key idea here is that color is not a good spectral predictor when the spectral space is too sparse. For the sake of illustration, let us consider a seven-channel light engine as the one that will be used later on the experimental section of this work. Every channel has 4096 intensity levels, so the number of different spectra that can be produced with such a light engine is an astonishing $4096^7 \sim 10^{25}$. Using dimensional analysis, we can now calculate the average number of spectra associated to a single color point. We can do this by assuming a grid in the CIE 1931-xy color space with basic area elements of the size $\Delta_x = \Delta_y = 10^{-4}$ (100 million of colors), giving rise to $\sim 10^{25}/10^8 = 10^{17}$ spectra per color. To put this number into perspective, 10^{17} not only is the number of different spectra that have the same color point, but it is also the age of the universe in seconds. It is only when we see these numbers that we realize that color is not a good predictor of SPD, because with no other information, if we try to minimize a color difference the SPD can crystallize into any of the 10^{17} different options.

But if we can narrow down the spectral space to a small subset of possibilities, it is possible to find positive correlates between color and spectral accuracy. This can be done for a particular case where the channel SPDs are known in advance (SPD presets measured at production time). The input variables are the target spectrum (and its associated color point) and the preset SPDs of the LED channels. The preknowledge of the preset channel SPDs is important because it can be utilized to narrow down the spectral possibilities for a given color. To do that, a first fitting algorithm is carried out with any available mathematical method borrowed from the literature,[17] i.e., a simple non-negative least squares method. This initial guess of the target spectrum would be errorless if the conditions (temperature junctions and aging) were the same as those present when the factory presets were measured. There are multiple ways these conditions may change; i.e., the junction temperatures when measuring the individual channel SPDs at production time are not representative of those obtained in real application cases. The heatsink thermal resistance may be different from the one used in the factory, the power supply may also change, and of course the aging processes that might have occurred would also differ.

Even though these differences between the estimated output spectrum (obtained using the preset channel SPDs) and the target spectrum may be important in some cases, the initial guess helps in reducing the sparsity of the spectral space, because now the distance between our initial guess and the final solution determined by temperature variations or aging processes has been dramatically reduced. Under these circumstances, where the whole spectral search space composed of about 10^{17} spectra has been reduced to a local region around the solution under (unreal) factory conditions, it turns out that color is now a good predictor of spectral shape. This can also be seen in this way: when the number of spectral possibilities has been dramatically reduced, a cooperative effect between color and spectral shape shows up, so that an effort to match the color point to the target color also has a positive effect on correcting the spectral shape toward the target.

In the following section, we perform an in-depth study of a proportional integral-derivative (PID) controller system having a colorimeter as a sensing element and acting over the pulse width modulation (PWM) signals of the LED channels to reduce the color difference to a target, while at the same time obtaining acceptable spectral errors between the output and target spectra.

2 Methods

For this work, we have used a LEDMOTIVE (model VEGA07) tunable light engine[18] that is composed of 48 commercial monochromatic LEDs (from Lumileds Luxeon C:[19] Red, PC Amber, Lime, Green, Cyan, Blue, and Royal Blue) arranged in 7 individual channels (a channel should be regarded as an arrangement of LEDs having the same peak wavelength), essentially spread all over the visible part of the visible spectrum (400 to 700 nm, see Fig. 1.). The different radiometric powers for each individual channels are (from red to blue) 0.95, 2.53, 2.2, 0.64, 1.18, 1.08, and 1.26 W.

A block diagram of the hardware can be found in Fig. 2. The control system is executed in a microcontroller in the light engine. The same microcontroller also handles the PWM signals, the communications, and the sensor acquisition system, which include readings from the power sensors, the temperature sensors, and the color sensor. The PWM constant current driver has a resolution depth of 12 bit. The overall system is controlled with a Python 3.4 program and a PC (Intel i5, 8 GB RAM) through a serial communications system RS-485.

Changes in the PN junction temperature and aging of the LEDs always lead to undesired fluctuations in the emitted SPD (that can be at short or long time scales depending on whether the originating mechanism is temperature or aging). These changes imply depreciation in both the luminous flux and wavelength shifts. Furthermore, the PWM modulation may not follow a perfect linear relationship with power, which may induce further errors in the output spectrum.

Our method of joint color and spectral matching can be succinctly summarized in the following steps.

1. Once a target spectrum has been set, either the firmware of the light engine or an external PC performs an optimization to find the PWM weights that constitute the best-fit to the target spectrum, considering the preset SPD channel calibration data using advanced heuristic algorithms.[17]
2. The controller sets the PWMs obtained from (1) to the light engine to emit a light based on the first calculation.
3. The embedded color sensor reads the mixed emitted light color point and reports this information to the controller.
4. The controller, with the target spectrum information and the measured color point, slightly modifies the PWMs set at the beginning in order to iteratively approximate the emitted color point to the target color point (defined by the target spectrum).
5. The process starts again from number (3) until both color points, target and emitted light, closely overlap.

In other words, the PWM weights of the channels are first adjusted to minimize a spectral shift with respect to the target spectrum and are second adjusted in a closed-loop to minimize color deviations with respect to the target color. This is equivalent to say that we are prioritizing color accuracy (closed-loop) against spectral fidelity (open-loop). This is a good strategy for the market of general lighting since

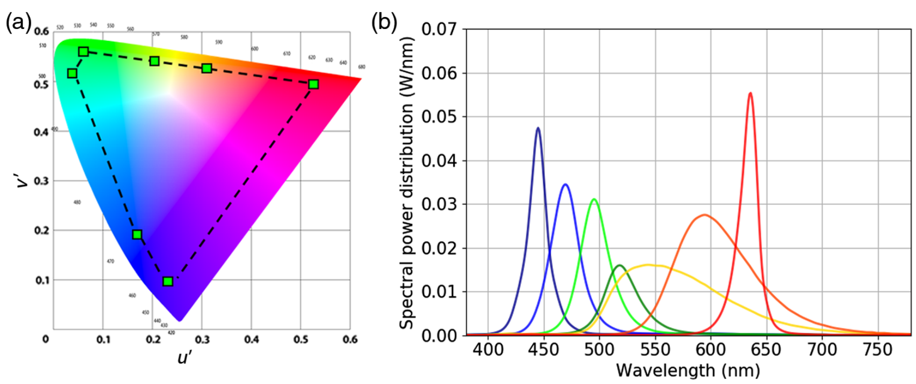

Fig. 1 CIE 1976 (u', v') coordinates of (a) the seven channels that define the color gamut and (b) the SPD of the seven LED channels.

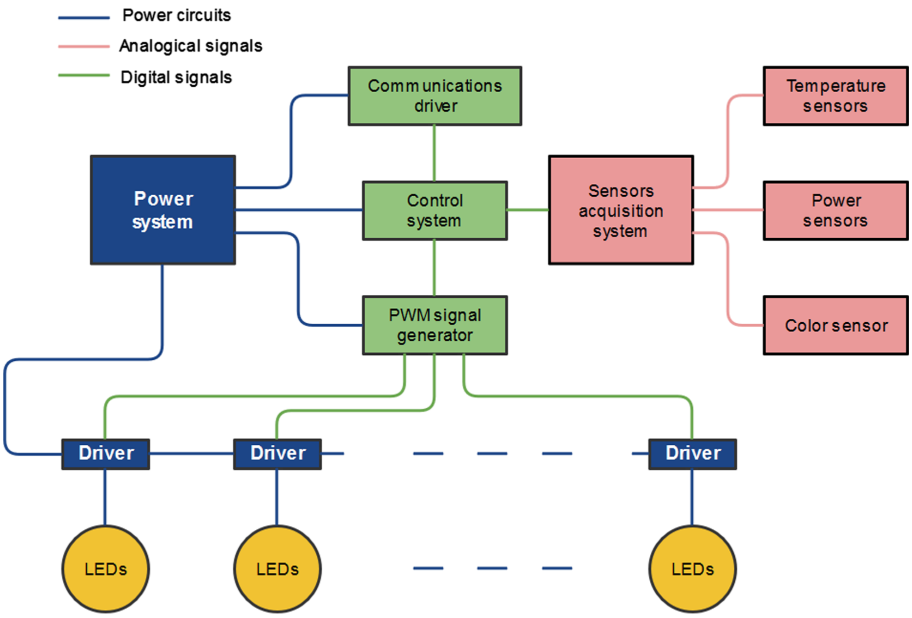

Fig. 2 Light engine hardware block diagram.

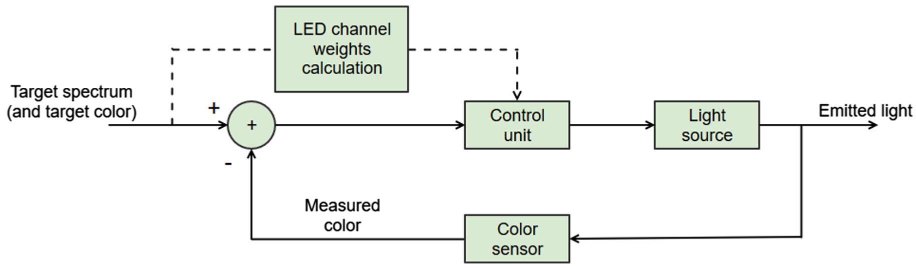

Fig. 3 Schematic of the implemented close-loop feedback system.

color reproducibility is critical because it is the most easily perceivable evidence of a light source malfunction. However, as pointed out before, the cooperative relationship between color and spectral shape arises when we have a decent (open-loop) initial guess of the spectral solution. So, even if the spectral solution is not optimized directly in a closed-loop as in our previous work,[17] the color closed-loop is enough for preserving the spectral shape to an acceptable accuracy.

In our implementation, the on-board color sensor is used as the sensing element for a PID control system. The light is collected from the diffuser element where all the light channels with different peak wavelengths are mixed. A polycarbonate waveguide (with an almost flat transmission response in the visible range) is in direct contact with the diffuser so that a number of rays are collected by the waveguide and are conducted to the entrance slit of the color sensor. The color information of the mixed light is then passed to and processed by the microcontroller to execute a new iteration of the PID algorithm. New PWM weights for each channel are generated at every step in the loop until the calculated color error is below an acceptable threshold. The spectral error is also monitored at each iteration step. A schematic of the modeled system is shown in Fig. 3.

At each iteration, the color of the emitted light is compared to the target color, and a decision-making block optimally determines how the PWM weights need to be modified so that the emitted light color gets closer to the target color. There are multiple ways to design this decision-making block. After some trial and error, we have observed that the best approach implies an initial determination of the LED channels that will reduce faster the error between the measured and the target color. For this, we have implemented a metrics that indicates the capacity that a channel has to influence the final color point. The metrics assumes that projections of vectors in the CIE 1976 L^*, u^*, v^* (CIELUV) color space (u', v')[20] constitute a good representation of the capacity of channels to impact convergence speed. As an example, a first vector can be determined corresponding to the observed color deviation between the emitted light and the target color points. In a similar way, for each light channel, a second vector can be determined corresponding to a color shift between the color point of the target spectrum and

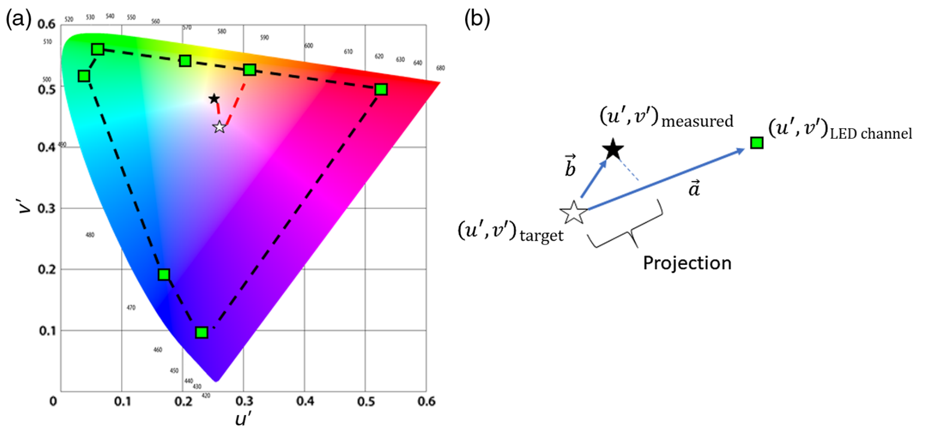

Fig. 4 (a) The target color point (white star), emitted light color point (black star), and all the preset channel SPD color points (green squares) in the CIE 1976 color space. (b) Schematic of the projection of the vector $\vec{b}$ (the color deviation between the emitted light color point and the target color point) into the vector $\vec{a}$ (the color deviation between the target and a LED channel color points).

the color point of the SPD for that light channel. Finally, we can compute the projection of the first vector onto the second vector for each of the light channels. The light channels that obtain a greater projection also have a higher capacity of shifting the color point toward the target color in less iterations. This projection metrics are passed as inputs to the feedback loop and indicate which channels need to participate at each iteration for the sake of a fast convergence to the solution.

A schematic of the different color points and vectors is shown in Fig. 4. The projection of one vector into the other, for the i'th LED channel, can be defined as

$$\text{projection}_i = \frac{\vec{a}_i \cdot \vec{b}}{|a_i|}. \tag{1}$$

Since there is no cross talk among the peak wavelengths of the preset SPDs, independent PID controls can be assigned to each LED channel. The PID controllers follow Eq. (2), where $u(t)$ is the signal, $e(t)$ is the current error [defined by Eq. (1) as the projection of the two vectors in the CIE 1976 color space], k_p is the controller path gain, T_i is the integral time constant, and T_d is the derivative time constant:

$$u(t) = k_p e(t) + \frac{k_p}{T_i}\int_0^t e(t)\mathrm{d}t + k_p T_d \frac{\mathrm{d}e(t)}{\mathrm{d}t}. \tag{2}$$

Since we are working with a digital signal, Eq. (3) can be used instead of Eq. (2). The PID has three different proportional, integral, and derivative parameters. The integral part acts on accumulated past errors and the derivative part is a prediction of future errors that depends on the rate of change. The PID parameters are generally found following a trial/error process until a fast convergence with a low overshoot is obtained (in our system, this tuning process resulted in values $k_p = 0.1$, $k_i = 0.1$, and $k_d = 0.05$).

$$u[n] = k_p e[n] + k_i \sum_{i=0}^{n} e[i] + k_d(e[n] - e[n-1]), \tag{3}$$

where $k_i = k_p/T_i$ and $k_d = k_p T_d$.

3 Results

The color difference was measured using the CIE 1976 L^*, u^*, v^* (CIELUV) color space (u', v'),[20] since it is a well-accepted metric for assessing the chromaticity of SSL products.[21]

When the feedback is off, there is a flux decrease in the SPD with time, which is stronger in the red region [see Fig. 5(a)]. Thus, the color coordinates show a trend toward more bluish colors, with a $\Delta u'v' > 0.005$ when comparing the spectra at time zero and after 1 h of operation [see Fig. 5(c)]. Even if we are in the best-case scenario where the spectrum is static and the time windows is only 1 h, the observed color shifts would never be acceptable by the lighting industry, which reinforces the message that cost-effective solutions based on optical sensors are required to increase their market acceptance.

When active, the implemented feedback monitors the system evolution and infers changes in the spectral shape to correct drifts. Figure 5(b) shows the time response of the feedback control, acting to preserve the color point over time. Starting from the calculated SPD (obtained with the preset SPD estimation of the channels), the feedback control acts at a millisecond timescale, modifying the PWM channel weights in order to get closer to the target color despite changes in both temperature and aging of the LEDs. Due to the colorimeter feedback, the color difference, after 1 h, is below $\Delta u'v' < 0.002$, while the SPD preserves its shape with a small error, as we will see later on.

To validate spectral errors, we have used an external spectrometer (CAS 120 by Instrument Systems). Figure 6(a) shows the emitted SPD at time zero (black solid line) generated by the best-fit to a 3000K blackbody SPD (blue dashed line). Although this is theoretically the spectral best-fit to the target, because of the local and immediate effect of

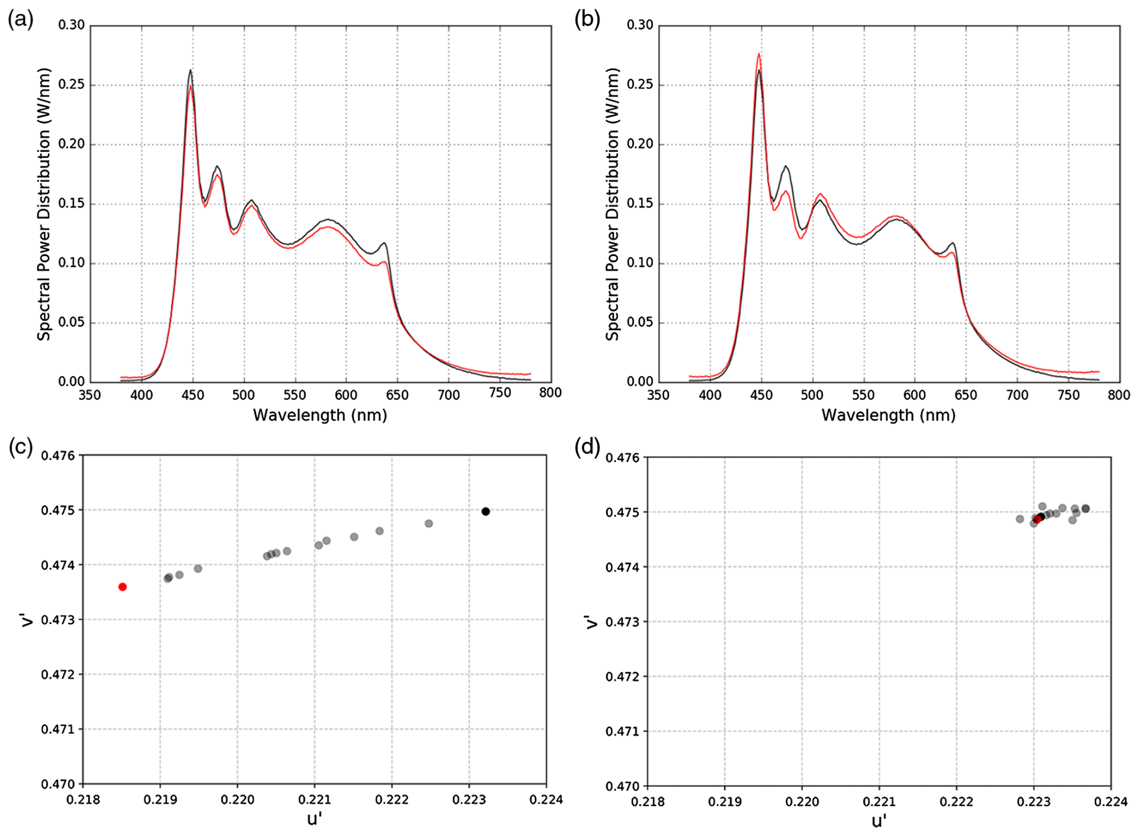

Fig. 5 Emitted SPD at time zero (black solid line) and after 1 h (red solid line) when the feedback is (a) off and (b) on. For the same spectra and time, the evolution of the color coordinates is shown from time zero (black dot), after 1 h (red dot) and the states in between are also shown (gray dots) in both cases when the feedback is (c) off and (d) on.

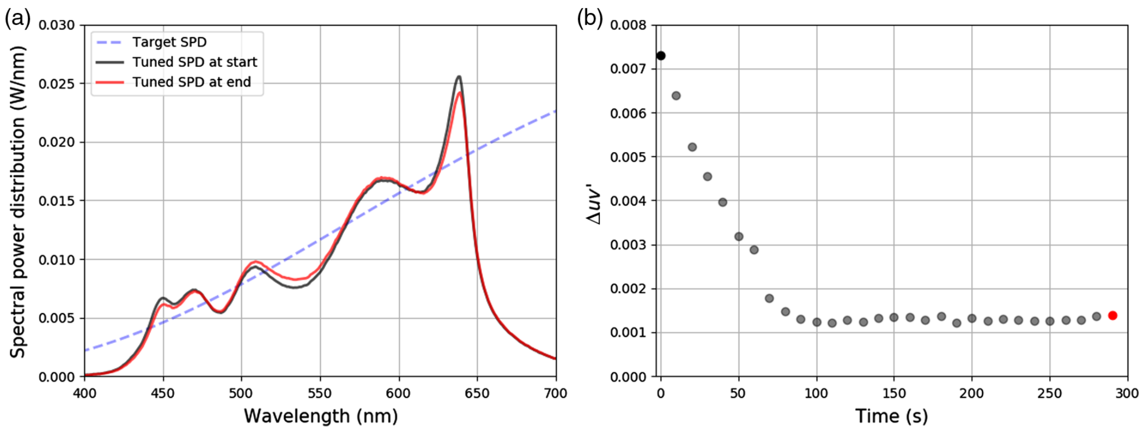

Fig. 6 (a) Emitted SPD at time zero (black solid line) generated by the best-fitting to a 3000K blackbody SPD target (blue dashed line) and emitted SPD after 300 s with the feedback function active. In (b), $\Delta u'v'$ between the target color point and the emitted light color point evolution for the same spectra and time.

the junction temperature distribution, the color point is at time zero far from the target color point [being the color difference $\Delta u'v' > 0.007$, see Fig. 6(b)]. When the feedback control is activated, it effectively corrects this color deviation, resulting in a $\Delta u'v' < 0.002$ in 60 s, which is way below the limit established by the lighting industry

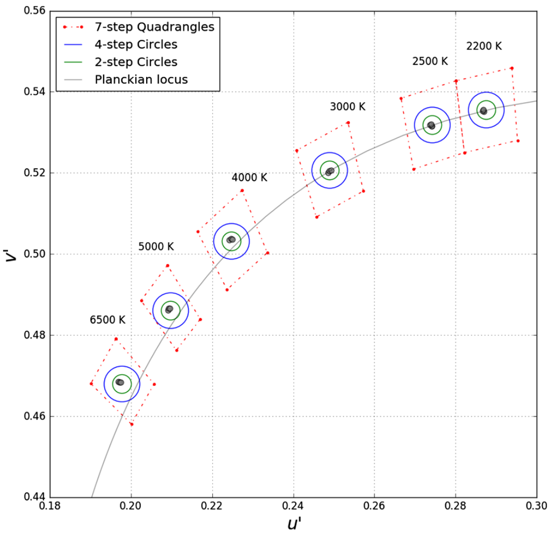

Fig. 7 Precision and accuracy of the proposed feedback system based on a cost-effective colorimeter (gray dots) when targeting different CCTs, and the industry standard limits (the seven-step quadrangles, the four-step ellipses, and the two-step ellipses).

standards.[21] At the same time, the SPD shape evolves to meet the color condition, applying slightly more power at some wavelengths and slightly less in others [see red solid line in Fig. 6(a)]. The interesting point here is that in this process the error incurred in the target SPD is as low as 10%, as measured by the mean absolute percentage deviation.[17]

The method presented here is not dependent on the selected target SPD or color point, and our results are general and can be applied to any desired target spectra. Figure 7 shows the precision and accuracy of the system for different CCTs and compares the results with the MacAdam industry standards.[21] For different CCTs across the Planckian locus, the color points are kept within two-step MacAdam ellipses. Moreover, the methods presented here hold also for different implementations of the spectrally tunable lighting system, for example using a different number of LED channels, and can be used to compensate for a failure of a small number of LEDs.

As a future work, it would be helpful to consider developing a temperature controller for the LEDs junction temperature to improve the first spectral match and the subsequent color minimization. Thus, the system would start from a color point closer to the target point and convergence to an optimal solution would be faster.

4 Conclusions

Despite the great possibilities of spectrally tunable light engines to create healthier living indoor environments, multichannel LED light sources still need to surmount intrinsic challenges associated with the technical aspects of using several LED channels, i.e., temperature and aging dependence of the spectral shapes and color points. This makes the development of these technologies and its application to real case scenarios difficult unless all these issues are attacked holistically. Even though there are some strategies in the literature that provide good results in spectral stability, they are based on expensive optical sensors, such as CMOS-grating spectrometers or interferometers, that prevent from an easy market adoption due to its price point. In this work, we provide for the first time a cost-effective solution that not only ensures color stability over time ($\Delta u'v' < 0.002$ over the product lifetime) but also warrants spectral accuracy (spectral errors to a target <10%), the cornerstone of all the recent advanced lighting applications such as human centric lighting.

Our methods provide tools and offer robustness to spectrally tunable solutions that are increasingly being used for different applications, by carefully engineering light spectra. These methods generally apply to systems having more than five channels, because the number of metamers representing a target color becomes unbearable, while at the same time the huge number of different spectra in the search space makes it possible to optimize for a target spectral solution fulfilling one or several preferred metrics. Museum lighting, health lighting, graphics arts industry, horticulture, or high-end offices with strong productivity needs are good examples of market spaces that demand highly accurate spectral solutions that are reliable and stable over time.

All the components utilized in this study have been selected to be suitable for mass-production and scale up significantly with volumes, which is the only manner they can make an impact and be directly applicable to the general lighting market.

Acknowledgments

This research received funding from the European Union's Horizon 2020 research and innovation program under Grant Agreement 766792; from the European Union Seventh Framework Program under Grant Agreement 619912; from the Government of Catalonia under Grant Agreement 2015 DI 081 (Pla de Doctorats Industrials); and from the Government of Spain under Grant Agreement DI-14-06883 (Plan Estatal de Investigación Científica y Técnica y de Innovación). The authors have no conflicts of interest in this paper and no other potential conflicts of interest to disclose.

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Aleix Llenas received his BS degree in physics from the University of Barcelona and his MS degree in photonics from Universitat Politècnica de Catalunya. He has worked in several international research projects in optics, photonics, and nanotechnology. He also worked for the NTT–Nippon Telegraph and Telephone Corporation, Japan, before joining the Catalonia Institute for Energy Research (IREC), where he is conducting research with multichannel LED light engines in collaboration with the R&D team at Ledmotive Technologies.

Josep Carreras received the BS, MS, and PhD (cum laude, hons.) degrees in physics from the University of Barcelona, Barcelona, Spain. He has authored over 60 articles in several SCI journals, holds two patents, and has participated in more than 20 different projects at the national and international level. He is also the president, founder, and chief technology officer of the spin-off Ledmotive Technologies. Since 2009, he has been with the IREC, Barcelona, as the leader of the Lighting Group, where he leads research on innovative concepts for energy-efficient lighting, color science and technology, simulations, photometry, and intelligent lighting with advanced communication and computation functionalities. He supervises several national and European projects in close collaboration with industrial partners.

Chapter 6

Third publication

Testing the use of spectrally tunable lighting systems to improve comfort, alertness and sleep quality in indoor working environments

Aleix Llenas, Anya Hurlbert, Florence Lam, Rohit Manudhane, Gaurav Gupta, Jason Giddings and Josep Carreras

Proceedings of the 29th CIE SESSION, 830-837.
Washington D.C., USA, June 14 - 22, 2019

International Commission on Illumination (CIE), Vienna, Austria.

https://doi.org/10.25039/x46.2019.PP29

ATTENTION¡¡
Pages 86 to 96 of the thesis, containing the publication mentioned above are available at the editor's web
http://files.cie.co.at/x046_2019/x046-PP29.pdf

Chapter 7

Fourth publication

Spectrally tunable LED light engines and the metamer optimization tool (MOTO)

Aleix Llenas and Josep Carreras

Proc. SPIE 10940, Light-Emitting Devices, Materials, and Applications, 109401L (1 March 2019)

https://doi.org/10.1117/12.2508714

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Pages 98 to 108 of the thesis, containing the publication mentioned above are available at the editor's web
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Chapter 8

Fifth publication

Methods to precisely generate arbitrary spectra using multi-coloured LED light engines

Aleix Llenas and Josep Carreras

Proc. SPIE 10693, Illumination Optics V, 106930M (28 May 2018)

https://doi.org/10.1117/12.2309494

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Chapter 9

Sixth publication

Enhancing comfort, alertness and productivity in indoor working environments using dynamic multi-channel led lighting systems that mimic daylight

Aleix Llenas and Josep Carreras

Proceedings of CIE 2018 "Topical Conference on Smart Lighting", Taipei (26 – 27 April 2018)

International Commission on Illumination (CIE), Vienna, Austria.

https://doi.org/10.25039/x45.2018.OP06

https://www.techstreet.com/cie/standards/enhancing-comfort-a
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ATTENTION¡¡

Pages 120 to 126 of the thesis, containing the publication mentioned above are available at the editor's web

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Appendix A

Other outreach and training actions

In addition to the publications and conferences listed before, during this PhD research project I had the chance to submit a patent application, publish other articles in collaboration with more researchers, and attend events to showcase our work and raise awareness about our technology. Our work received attention from lighting and photonics news agencies and some articles featuring our results were also published.

Besides, during this three years I had the change to attend several training courses to complement my research and improve my innovation management and entrepreneurship skills.

Some of those actions are listed below:

A.1 Other publications

- **Aleix Llenas Farràs** and Josep Maria Carreras Molins "CONTROL DE DISPOSITIVOS DE ILUMINACIÓN" ("Controlling lighting devices"), Priority patent PCT/ES2017/070041, application filed by Ledmotive Technologies, S.L. (2017).

- **Aleix Llenas**, Jorge Higuera and Josep Carreras "Tendencias en sistemas digitales de iluminación y conectividad," Revista Luces CEI, Número 60, 26-34, Comité Español de la Iluminación (Febrero 2017). `https://www.doi.org/10.5281/zenodo.3274388`

- Jorge Higuera, **Aleix Llenas** and Josep Carreras "Trends in smart lighting for the Internet of Things," arXiv preprint arXiv:1809.00986 (2018).

A.2 Other communications

- **Aleix Llenas** and Josep Carreras "Hands on digital light: Spectral design tools for human centric lighting and related applications," Photonics Media Webinar, September 2019. Online webinar.
  `https://www.photonics.com/Webinars/Hands-on_Digital_Light_Spectral_Design_Tools_for/w190`

- **Aleix Llenas** and Josep Carreras "Llum digital i eines de disseny espectral," 3^a Jornada UOC Industria 4.0, Universitat Oberta de Catalunya, Barcelona (2019). Oral communication.

- **Aleix Llenas** and Josep Carreras "Enhancing comfort, alertness and productivity in indoor environments using spectrally tunable LED light engines that mimic daylight," InnoEnergy PhD School Annual Conference 2018 "Engineers of the future: going beyond technology", Budapest (2018). Poster communication.

- **Aleix Llenas**, Francisco Javier Campoy and Josep Carreras "Feedback controller for accurate spectral fidelity against thermal junction variations and LED luminous flux depreciation." Workshop HI-LED "Spectrally - Tunable LED and OLED lighting" in the LpS 2016 - LED professional symposium, Bregenz (2016). Poster communication.

- **Aleix Llenas** and Josep Carreras "Spectral and hyperspectral applications of multi-channel LED light engines," Debat IREC, Institut de Recerca en Energia de Catalunya (IREC), 2016. Oral communication.

A.3 Our work in the news

The work done had some impact in specialized optics and lighting websites, and several news articles and one interview were done. Some of those are listed below:

- "Move over Alexa, These Smart Lights Don't Need You to Tell Them When to Shine". SPIE Professional Magazine. September 2019.
  `https://spie.org/news/move-over-alexa`

- "Measuring and Self-Adjusting Spectral Power Distribution of LED Systems". Novus Light Technologies Today. News article and interview. Written by Sandra Henderson, 18 April 2019.

https://www.novuslight.com/measuring-and-self-adjusting-spectral-power-distribution-of-led-systems_N9193.html

- "Tomando el control de la iluminación de espectro variable en aplicaciones para Human Centric Lighting". Smart Lighting. News article. Written by José Enrique Álvarez, 2 April 2019.
https://smart-lighting.es/tomando-control-la-iluminacion-espectro-variable/

- "Computational Methods Enable Solid-State Lighting to Self-adjust". Photonics Media. News article. June 2019.
https://www.photonics.com/Articles/Computational_Methods_Enable_Solid-State_Lighting/a64558

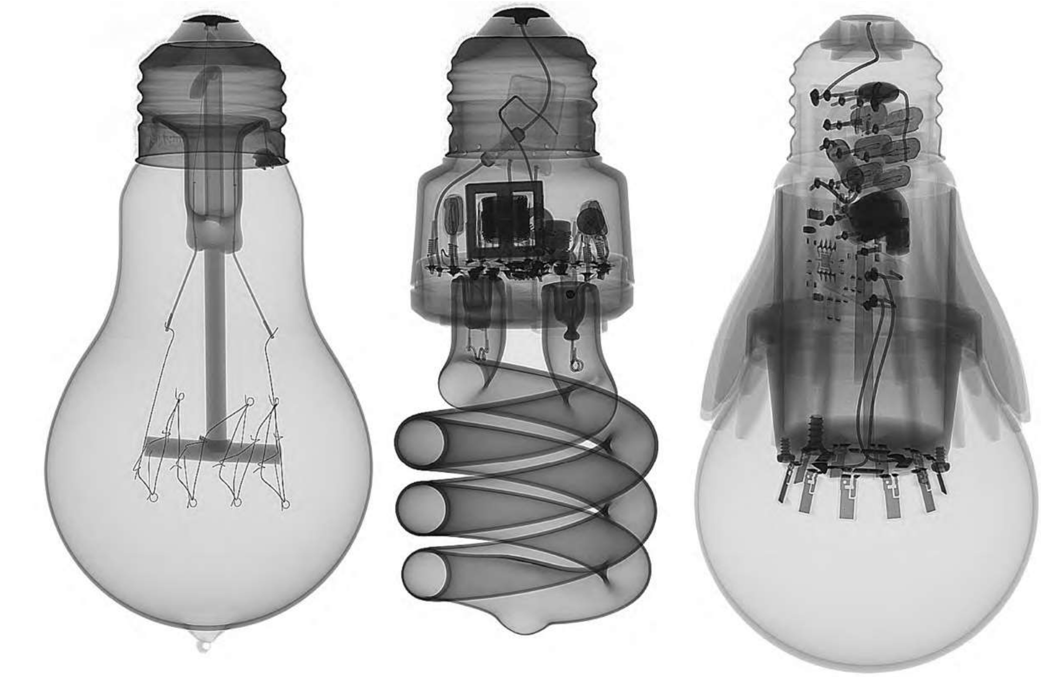
- "Barcelona hospital features spectrally-tuned lighting". Lux Review. News article. July 2019.
https://luxreview.com/article/2019/07/barcelona-hospital-features-spectral-tuned-lighting

- "Arup office transformed in tuneable light study". Lux Review. News article. September 2019.
https://luxreview.com/article/2019/09/arup-office-transformed-in-tuneable-light-study

In the following pages are shown a set of screenshots of some selected news articles.

A.3.1 SPIE Professional Magazine

TECHNOLOGY



Credit: Herminso Villarraga-Gomez, "The Evolution of Electric Lighting"

Move Over Alexa, These Smart Lights Don't Need You to Tell Them When to Shine

The role that light plays in regulating the 24-hour circadian rhythm is well understood by scientists, and so broadly accepted by the mainstream population that there is increasing commercial demand for more human-centric lighting in residences and offices.

Human-centric lighting (HCL) can be used to create dynamic indoor environments that mimic daylight patterns with respect to human circadian rhythms and physiology. For example, the stimulating effects of bluer frequencies are welcome during daytime hours, whereas amber and red frequencies are relaxing, and therefore more desirable in the evenings. HCL is enabled by the maturity of LED lighting, which enables finely tuned control over the color temperature of the light, as well as spectral power and brightness.

In addition to enhancing our sleep and wellbeing, solid-state lighting benefits are evident in the ongoing development of applications in medicine, imaging, agriculture, communication, transportation, and museum lighting. Some of these applications require highly precise light spectra that don't produce optical power variations or shifts in color over time.

But as a bulb ages or a junction heats up, the spectral distributions fluctuate. The amber spectrum may weaken before the blue spectrum. But wouldn't it be great if a bulb could recognize, by itself, that its amber channel was fading? And if, after recognizing this fact, it could increase the pulse-width modulation weight of the amber channel so that it continues to meet the spectral power distribution required for a specific setting?

Researchers Aleix Llenas from Catalonia Institute for Energy Research (Spain) and Josep Carreras from Ledmotive Technologies (Spain) have done just that. Their work, recently published in the SPIE journal *Optical Engineering*, addresses two lighting challenges: how to keep temperature changes and age-based deterioration from impacting a light emission's strength, consistency, and color, as well as providing a reliable, internal, self-monitoring method.

They use a fast-computation annealing algorithm to determine channel weights of a targeted SPD, such as one designed for optimal lighting at 5 p.m. In conjunction, a microprocessor in the light provides a closed-loop control system that monitors and corrects the spectral output, compensating for shifts due to temperature changes or wear and tear on the LED. In effect, the light can keep an emitted spectrum constant and stable over time.

Daniel LeMaster, associate editor for *Optical Engineering*, believes that the research showcases significant advances in terms of lighting technologies. He says, "This method to monitor and quickly compensate for the colorimetric issues that arise from junction heating and LED aging will be of great utility in the global LED lighting market."

The intelligence and spectral awareness of these LEDs create new possibilities for healthier living spaces by giving lighting designers complete control over the visible spectrum, at any time of day. ■

Read the article: **spie.org/SmartLights**

A.3.2 Novus Light Technologies Today

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Measuring and Self-Adjusting Spectral Power Distribution of LED Systems

Written by Sandra Henderson 18 April 2019

Researchers from the Catalonia Institute for Energy Research (IREC) at the University of Barcelona and its spin-off Ledmotive Technologies in Spain have combined two computational methods to enable solid-state lighting (SSL) to measure and self-adjust based on conditions. The two-pronged approach, which shows an LED lighting system's ability to maintain consistency and stability over an extended period of time, allows for high spectral fidelity and short computational processing times for spectrally tunable light sources and could mark a crucial advance in light-based technologies.

The need for reliable, stable, easy-to-mass-produce LED

The lighting industry is undergoing profound transformation. Solid-state lighting (SSL) and, more specifically, LED have made it possible to sculpt the spectral power distribution of light depending on the application. However, temperature variations and aging processes cause spectral and color shifts in LED. The semiconducting materials LED are made of are particularly temperature sensitive. The lighting industry, nevertheless, requires the devices to be reliable and batch-to-batch reproducible. "We believe that, even though some workarounds are used that consist in storing look-up tables representative of the physics of these processes in the firmware at production time, a definitive solution necessarily implies an optical feedback," says Josep Carreras, PhD, president and CTO of Ledmotive Technologies. "From this achievement, the spectral matching algorithms form an essential groundwork to build upon."

The research team tackled a two-fold problem with this work: "First, we implement fast algorithms to adjust the light spectrum of different LED, i.e., colors or wavelengths, to a given target spectrum. And secondly, we design a feedback control that warrants the stability of the light output over its lifetime."

What is new in this research is that the scientists have been able to establish the right tradeoff between spectral and color accuracy and the short computational times required by practical applications. "Obviously, the main goal is to end up having a lighting device that is suitable for mass production," Carreras points out. "So we have taken special care in the fact that all the proposed algorithms run as firmware pieces executed by cost-effective micro-controllers."

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NEXT

A crucial advance in lighting science and technology

Spectral control is a new field in lighting science and technology. “Some years ago, the spectrum of light was determined by the materials we were using,” Carreras says. “Today, we can already design spaces and applications with purpose by changing not only the intensity but also the energy of the photons that we use, the wavelength.” Many different application areas can benefit from such fine control, from healthcare to workplace productivity, retail illumination, museum lighting, photography, the film industry, horticulture and even scientific-grade instruments for research institutions, according to the light-technology expert.

Designing better solid-state lighting technologies in the future

The new computational methodologies could specifically help to improve the design of the next generation of solid-state lighting technologies, Carreras agrees: “There is a great consensus in that the next generation of SSL technologies would involve some type of spectral control,” he says. “We are now in the phase of understanding how to utilize spectral control to our benefit.”

In the past, Carreras’ work has focused on fundamental research involving the interaction of light and matter, namely photon generation in quantum dots. While he says he found the work fascinating, the time to market, if it could even be defined, was tremendously long. “Recently, my research is focused on practical topics that can see the light in a timescale that goes from a few months to a couple of years,” he says. “We are already using the algorithms presented in this paper in commercial products at Ledmotive.“ The Barcelona-based spin-off company commercializes spectrally tunable light sources.

What is next

Carreras believes the most exciting part of SSL research and development is yet to come. “As I mentioned, we are building a solid ground for spectral lighting to be a reality, but we are also working on an online platform that will allow any lighting designer or even non-specialist to spectrally design any space or application,” he reveals, adding that the innovation is a user-friendly platform made of two basic components: the so-called Metamer Optimization Tool (MOTO) for static illumination spectra and the 24-hour light-cycle optimizer (CYCLO) that generates dynamic (spectrally optimized) light sequences in the blink of an eye. Right now, both tools are being beta-tested but will be available soon.

The paper "Arbitrary spectral matching using multi-LED lighting systems" is published in the SPIE journal *Optical Engineering*.

Written by Sandra Henderson, research editor *Novus Light Technologies Today*

Labels: Self-Adjust Spectral Power Distribution, LED Systems, Catalonia Institute for Energy Research, IREC, Ledmotive Technologies, solid-state lighting, Josep Carreras, spectral matching, multi-LED lighting systems, agriculture, healthcare

◄ Back to Light Research

A.3.3 Photonics Media

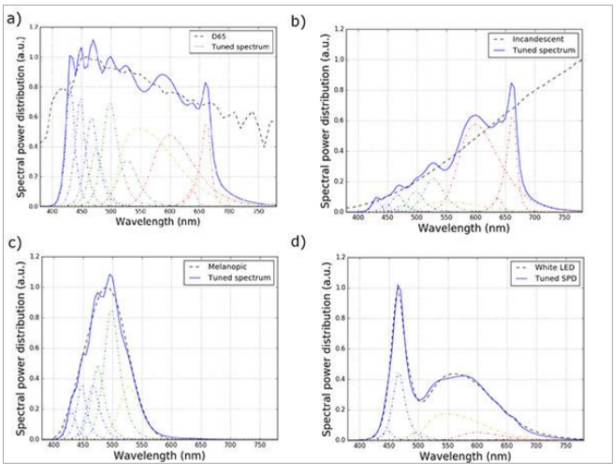
Computational Methods Enable Solid-State Lighting to Self-adjust

Researchers from the Catalonia Institute for Energy Research (IREC) and Ledmotive Technologies have developed a two-step approach to precisely and efficiently generate spectral power distributions (SPDs) using multichannel LED engines. This approach could be used to help resolve temperature and color shifts and flux variations in LED emissions.

The team addressed two challenges: how to keep temperature changes and age-based deterioration from affecting a light emission's strength, consistency, and color; and how to provide a reliable, internal, self-monitoring method that is able to keep an emitted spectrum constant and stable over time.

First, the researchers studied different algorithms that could be used to find the channel weights that would best match a target SPD. They found that a simulated annealing algorithm delivered good results with regard to spectral fidelity while requiring extremely low computation times.

Then, the researchers implemented a closed-loop control system to monitor and correct spectral deviations in the emitted light and to compensate for spectral shifts due to temperature changes or depreciation of the LEDs.



These four examples show (a) the best fit (blue solid line) to daylight D65, (b) an incandescent spectrum, (c) the melanopic, and (d) a white LED spectrum (Ph-LED YAG) (dashed black lines) made by optimizing the weights of the 10 different channels of the LED light engine (colored dash-dot lines). In all cases, the spectra were normalized and are shown in arbitrary units. Courtesy of Aleix Llenas, Catalonia Institute for Energy Research, and Josep Carreras, Ledmotive Technologies, Barcelona, Spain.

These two steps can be used independently, but the researchers said that only a combination of both steps will offer both fast computational times and high spectral accuracy and precision. Some solid-state lighting (SSL) applications — medicine, agriculture, imaging, and museum lighting, among others — require highly precise light spectra that will not produce optical power variations or shifts in color over time. The team's methods set a general framework for multichannel SSL systems and could be applied to different systems and lighting technologies.

According to *Optical Engineering* associate editor Daniel A. LeMaster, the research showcases significant advances in terms of lighting technologies: "This method to monitor and quickly compensate for the colorimetric issues that arise from junction heating and LED aging will be of great utility in the global LED lighting market."

The research was published in *Optical Engineering*, a publication of SPIE (https://doi.org/10.1117/1.OE.58.3.035105).

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Arup office transformed in tuneable light study

The Arup experiment used technology from Spanish manufacturer Ledmotive, which consisted of an LED-based module made with seven different independent colours. One of the colours was centred at the peak of the melanopsin curve, a measure of the production of the body's natural sleep-wake hormone.

LEADING ARCHITECTURAL and building services consultancy Arup has conducted a pilot study at its London office into the behavioural effects of dynamic spectrally-tunable lighting.

The nine-week trial experiment was designed to understand how 'light sculpting' could impact biological and psychological processes.

The experiment used technology from Spanish manufacturer Ledmotive, which consisted of an LED-based module made with seven different independent colours.

One of the colours was centred at the peak of the melanopsin curve, a measure of the production of the body's natural sleep-wake hormone.

Dynamic custom-made light spectra sequences were applied throughout the day.

These were either spectra designed to mimic natural daylight changes or to achieve a certain level of non-visual stimulation.

The office windows were blocked to avoid people being exposed to sunlight during work hours, and different light spectra, designed by a team of scientists, were used.

One example is shown in graph 1, focusing on the dynamism of the melanopic response.

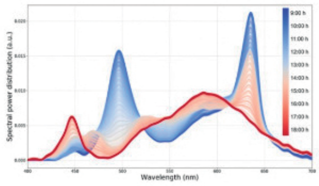
Subjective and objective tests were then performed to assess the behavioural responses resulting from exposure to the special lighting, and to compare these with responses to a traditional lighting system.

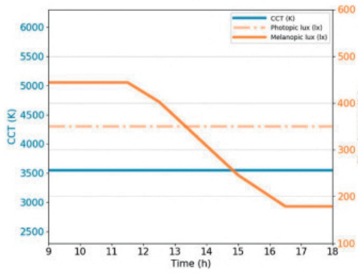
The office windows were blocked to avoid people being exposed to sunlight during work hours, and different light spectra, designed by a team of scientists, were used

The effectiveness of a given light spectrum in activating the so-called non-visual pathway – light receptors in the eye which aren't connected to 'seeing' – was quantified by its melanopic lux in addition to visual factors such as photopic lux or correlated colour temperature (CCT).

In graph 2 is shown one of the specifications of an experiment.

While maintaining CCT and lux value, the spectral output was targeted to induce large variations in the melanopic lux.

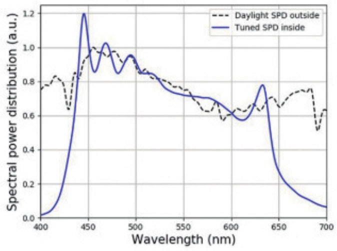


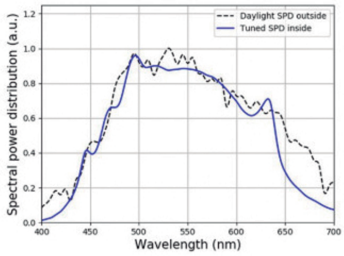


The 'non-visual' response

Light allows people to orient, see the shape and the colour of objects via the classical visual pathway in the brain. However, over the last two decades it has become increasingly more evident that people also respond to light in non-visual ways. The non-visual pathway is responsible not only for regulating our daily rhythms (such as body temperature, melatonin secretion and overall sleep/wake cycle) but also for modulating cognitive function, attention and mood for instance.

Spectral variations in light beyond tuneable white, can trigger distinct non-visual effects which can affect thus biological and psychological processes and it is important for health and wellbeing to take these into account in designing the right spectra (or light) for the right time of the day.Lighting installations in offices and buildings are typically static and specified in terms of their effects via the classical visual pathway (e.g. chromaticity or brightness, colour rendering, correlated colour temperature, illuminance level or glare to mention few).





From top: graphs 1 to 4 show the spectral output, colour temperature, and two spectral power distributions used in the experiment

The results will be presented at the LuxLive 2019 event in London in November to raise awareness of the importance of a circadian lighting design and the importance of having a full spectral control and not just tuneable white lighting.

It's believed to be the first office installation in the world, where outdoor daylight streaming from a spectrometer readout was fed into an indoor area.

An IoT spectrometer, located at the rooftop of the building, was used to capture light outdoors and feed it into the Ledmotive lighting system via the cloud, effecting the lighting directly inside the office.

Subtle spectral changes outside were translated into subtle and smooth spectral changes inside the office.

The team behind the project include: Anya Hurlbert, Professor at Newcastle University, Newcastle; Florence Lam, Arup Fellow, Director Global Lighting Design at Arup, London; Rohit Manudhane, architect, daylighting and lighting designer at Arup, London; Castan Architectural Lighting; Ledmotive.

- Learn more about the project at LuxLive 2019 exhibition, taking place on Wednesday 13 November and Thursday 14 November 2018 at ExCeL London. Entry is free if you pre-register HERE.

LUX LIVE 2019

A.4 Training courses

As a PhD candidate, I also had the chance to access a comprehensive set of training courses to complement my research.

- Managing Innovation and Entrepreneurship. ESADE Business School. Barcelona, June 2019. 7 ECTS.
- Data Science and Big Data. Postgraduate course, Universitat de Barcelona. Barcelona, September 2016 to July 2017. 10 ECTS.
- Teamwork and Leadership. AGH University of Science and Technology. Krakow, April 2018. 3 ECTS.
- Law for academic innovators. Uppsala University. Uppsala, April - May 2019. 5 ECTS.
- Energy Economics. Grenoble École de Management (GEM). Grenoble, March 2018. 3 ECTS.
- Smart grids. AGH University of Science and Technology. Krakow, November 2018. 3 ECTS.
- Formació en competències transversals. CT Formación, Pla de doctorats Industrials de la Generalitat de Catalunya. Barcelona, November 2017.

Appendix B

Product datasheets

B.1 The SPECTRA TUNE LAB datasheet

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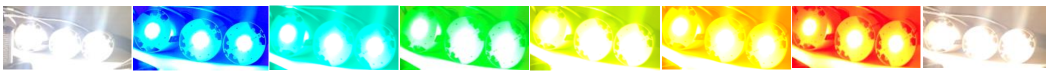
SPECTRA TUNE LAB

Light Engine for Scientists



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SPECTRA TUNE LAB
Light Engine for Scientists

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SPECTRA TUNE LAB
Light Engine for Scientists

DESCRIPTION

The SPECTRA TUNE LAB device is the most versatile LED light engine from LEDMOTIVE. The system can deliver either white light or any light spectrum obtained from the modulation of each of its different wavelength channels. No warm up time is required, and light can be dimmed from 0% to 100% for each channel with a resolution depth of 12 bits (4096 steps).

The standard SPECTRA TUNE LAB is equipped with 10 different types of colored LEDs. Optionally, the customer can tailor its own wavelength configurations (up to 12 different LED channels) by filling a *Customer Special Request* form.

LEDMOTIVE patented technology (Patent PCT/EP2011/050002) warrants spectral precision and accuracy as well as stability over time, through a CMOS-based onboard spectroradiometer.

The system can emit different spectrum every 10 milliseconds on average[1].

Figure 1. SPECTRA TUNE LAB front and rear view

SPECTRA TUNE LAB – Features

- High power multi-spectral LED light engine
- Independent color channel dimming
- Precise, accurate and stable light emission
- Fast spectral transition in asynchronous operation mode
- Compact and light weight system
- No warm up required
- Mounting accessories compatible w/ standard optical tables & ¼ thread for tripod mounting
- Compatible with LIGHT CREATOR© digital light IoT and spectral sharing platform
- µWAVE Software© with the SPECTRA TUNE LAB basic operation controls
- Optional: RESTful API
- Optional: C-mount adaptor that allow to connect standard compatible light guide connectors
- Multiple SPECTRA TUNE LAB can be connected in serial using the data in, data out connector

[1] asynchronous operation mode

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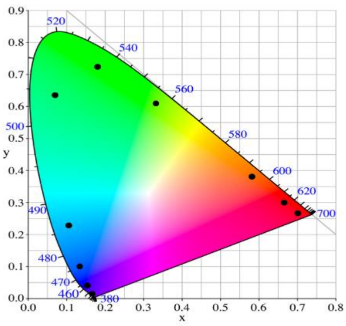
LED-ENGINE: STANDARD CONFIGURATION

Below is a summary of the standard configuration. Values may change slightly depending on the current availability of the different wavelength (color) or flux bins.

Channel	Nº of LEDs	Color	Peak Emission (nm)	radiometric value (W)	Photometric Value(lm)	FWHM (nm)
CH 1	2	UV	429	0.74	13.4	16
CH 2	2	Royal Blue	446	0.95	35.8	22
CH 3	3	Dark Blue	465	0.94	73.9	27
CH 4	3	Blue	475	0.89	97.5	27
CH 5	5	Cyan	505	0.98	319.3	34
CH 6	5	Green	525	0.77	389.2	37
CH 7	10	Lime	550	2.75	1256.4	115
CH 8	12	PC Amber	595	2.76	990.9	81
CH 9	2	Red	638	0.62	101.9	21
CH 10	4	Deep Red	660	1.25	81.4	23

Figure 2. Generic features of the standard SPECTRA TUNE LAB light engine



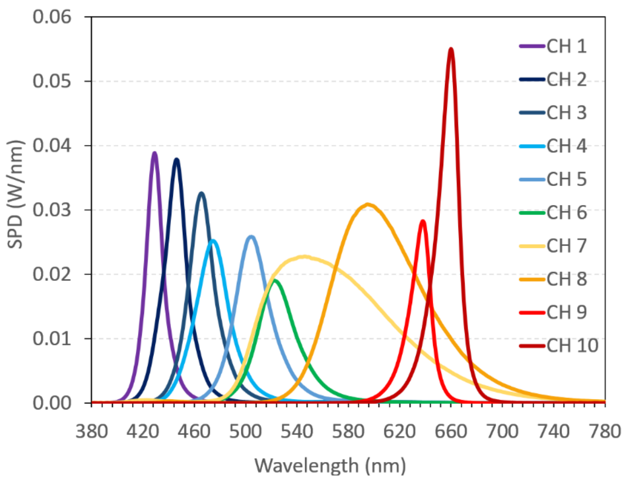


Figure 3. (left) CIE 1931 xy coordinates of the 10 channels that define the color gamut and (right) Spectral Power Distributions (SPDs) of the LED channels

All active channels are mixed at the exit plane of the LED module, which provides the SPECTRA TUNE LAB with a smooth (highly uniform in color) light with a Lambertian pattern profile.

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SPECTRAL MODULATION

Example of two different spectral modulations that best reproduce a blackbody radiation curve at two different temperatures (2700 K and 6500 K):

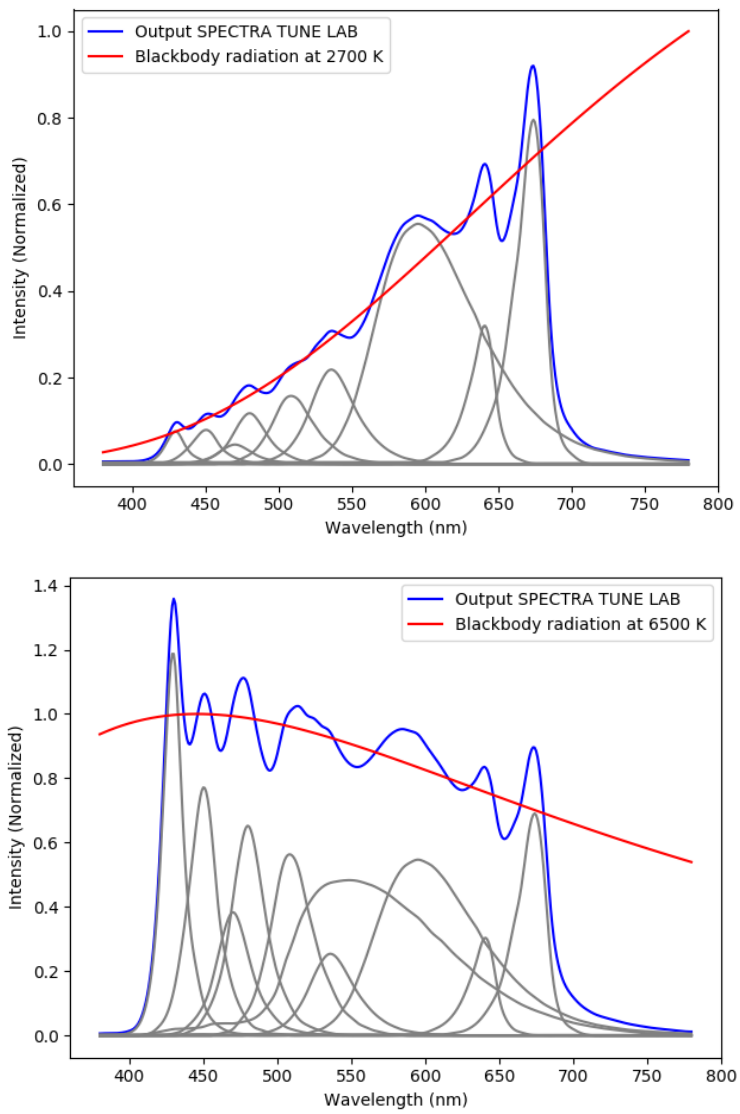

Figure 4. Example of two different spectral fittings (2700 K and 6500 K blackbody radiators)

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LED-ENGINE: CUSTOMER SPECIAL REQUEST

Even though the standard version comes with 10 wavelength channels, the SPECTRA TUNE LAB has indeed 12 physical drivers which can be grouped in different channels. Each of these drivers can control a specific number of LEDs as shown in the table below.

Physical Driver	Nº of LEDs	LED type
Dr 1	2	See Table A
Dr 2	2	See Table B
Dr 3	3	
Dr 4	3	
Dr 5	5	
Dr 6	5	
Dr 7	5	
Dr 8	5	
Dr 9	6	
Dr 10	6	
Dr 11	2	
Dr 12	4	

Table A	peak wavelength range
UV-VIS	from 380 nm to 425 nm
VIS	from 440 nm to 670 nm
NIR	850 nm, 940 nm

Table B	peak wavelength range
VIS	from 440 nm to 750 nm

Figure 5. Different types of LEDs and number of LEDs in each driver for a Customer Special Request option

Based on a Customer Specific Request (CSR), different wavelength channel arrangements can be ordered to build a customized light engine, with wavelength channels spanning from the long ultraviolet to the near infrared (please contact sales for a quotation). Further developments may require a full new design of the LED PCB and need to be discussed in detail with our technical team.

Please contact our Sales team at sales@ledmotive.com to find out more about how to define your special requests and get the perfect multi-channel solution that suits best your needs.

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SPECTRAL PRECISION, ACCURACY and STABILITY

LEDMOTIVE patented technology allows the SPECTRA TUNE HCL to emit light spectra with **unprecedented accuracy and precision**. It also offers perfect stability over time thanks to the on-board CMOS spectrophotometer and the associated **feedback loop control algorithms**.

The proper indicator for the goodness of a spectral fit is the Mean Absolute Percentage Deviation (MAPD). The MAPD gives an idea of the percentage error measurement between a target spectrum (after applying a non-negative least square method to the channel's PWM signal) and the measured spectrum. The MAPD expression is given by

$$MAPD = \frac{100}{nº\ of\ points} * \sum_{i=0}^{nº\ of\ points} \left| \frac{\left(SPD^{i}_{actual} - SPD^{i}_{target}\right)}{SPD^{i}_{target}} \right|$$

The table below shows MAPD values obtained from different light spectra and output powers. When the feedback loop is enabled, a significant improvement can be seen and a very low MAPD is obtained.

Spectral errors are kept below 3% with the optical feedback ON. In cases, this translates into color deviations Duv' lower than 10^{-4} or well below a 4-step Mac Adam (ANSI C78.377-2015 specifications).

MAPD	W/O feedback loop	W/ feedback loop	Duv' (color matching feedback)	% improvement
TEST spectrum 1- low power	4	3	8.00E-04	25%
TEST spectrum 1- medium power	2	2	9.00E-04	0%
TEST spectrum 1- high power	3	2	2.30E-03	33%
TEST spectrum 2- low power	6	4	3.50E-03	33%
TEST spectrum 2- medium power	3	2	4.00E-04	33%
TEST spectrum 2- high power	2	2	8.00E-04	0%
TEST spectrum 3- low power	8	4	4.70E-03	50%
TEST spectrum 3- medium power	3	2	5.00E-04	33%
TEST spectrum 3- high power	2	2	2.00E-03	0%

Figure 6. MAPD values for different spectra with and without the feedback loop control respectively and its % of improvement

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SPECTRAL SWITCHING TIME

The SPECTRA TUNE LAB works in synchronous mode by default.

In this mode, the SPECTRA TUNE LAB acknowledges receipt of all the commands sent by the LIGHT HUB before it accepts a new instruction, so that "collisions" between messages can be detected and duly corrected. Typical response times of this operation mode is 250 milliseconds approximately. Most of the commands in the SPECTRA TUNE LAB are programmed to work in synchronous mode.

Whenever the application requires fast switching times, the SPECTRA TUNE LAB can be set to work in asynchronous mode[2]. In that case, the SPECTRA TUNE LAB does not send an acknowledge receipt signal to the LIGHT HUB, making it possible a sort of spectral streaming in real time. Typical average time between consecutive light spectra operating under the asynchronous mode is less than 10 milliseconds (1 spectrum every 10 milliseconds).

THERMAL PROTECTION

The SPECTRA TUNE LAB incorporates a temperature protection control that is enabled by default. In the unlikely event of PCB overheating (fan or dissipation failure, harsh environments, etc.), the LED module will automatically reduce its luminous flux and consequently the consumed electrical power to keep the temperature within a safety range. In this way, the optimal working conditions that warrant the lifespan of the LED engine and its components are always preserved.

ELECTRICAL SPECIFICATIONS

Nominal Input Voltage	24 V DC (Constant Voltage) ±5%
Max. Power Input	80 W (limited by firmware)
Max. Current Input	3.3 A* (limited by firmware)
Data connector	RJ9
Data communication control	LEDMOTIVE proprietary protocol**

* fuse protection at 3.5 A
** based on a communication bus EIA-485 (also known as RS-485)

Together with the SPECTRA TUNE LAB, a power adaptor is provided to convert from a 100-240 V AC, 50/60 Hz, 1.3 A to a 24 V DC, 3.75 A (90 W max) used in the light engine and another power adaptor to convert from a 100-240 V AC, 50/60 Hz, 1.3A to a 5 V DC, 2.4 A (12 W max) used in the LIGHT HUB.

[2] The optional RESTful API is necessary to make use of the asynchronous mode. Go to page #10 for more details

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CONTROL SOFTWARE

With every SPECTRA TUNE LAB, a PC/Laptop a µWAVE Software© license is provided to control the device properly. For research applications that need advanced programmatic functionalities please check the optional RESTful API described in *Appendix 2*).

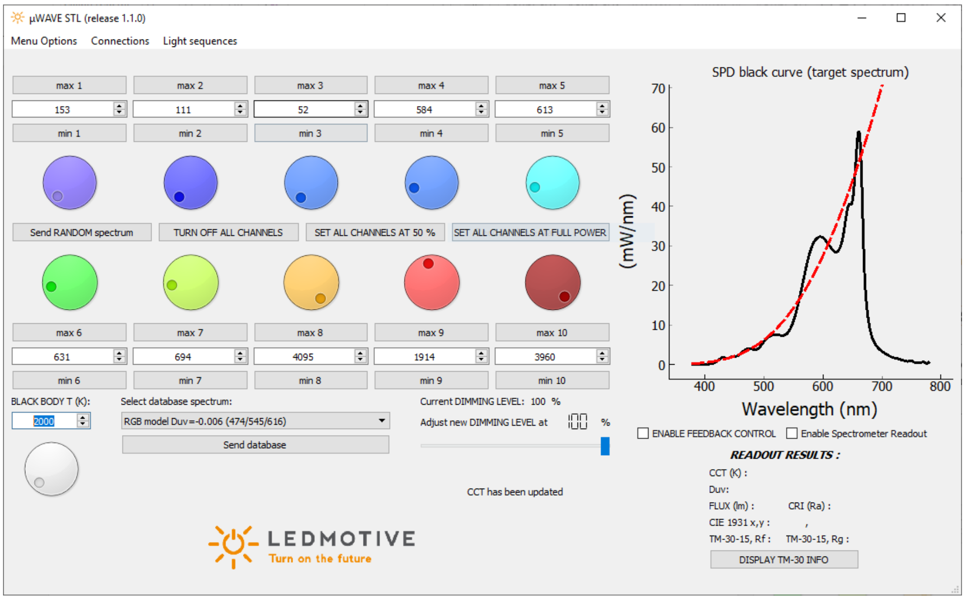

Figure 7. Screenshot of the µWAVE Software

Computer requirements:

- 64-bit Operating System
- Windows version; preferred WIN 8 and above

Features:

- Change the amplitude of each channel to create a specific spectrum
- Dim the light output
- Save and import light spectra
- Playback spectra from the spectral database
- Create, save and reproduce light sequences (dynamic streaming of light spectra) by adding different light spectra to the sequence pool

Please contact our sales team at sales@ledmotive.com if an executable version with special requests (MAC version or 32-bit OS) is needed.

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OPTIONAL: RESTful API

To provide the user with full programing flexibility in the operation of the SPECTRA TUNE LAB, a RESTful API is available for the LIGHT HUB. The LIGHT HUB can be accessed using the HTTP protocol under any programming language (C, C++, C#, Python, MATLAB, Java, JavaScript, etc.).

Some details are provided in *Appendix 2*, but an Application Note explaining in full the RESTful API commands is available on request. Please contact the sales team at sales@ledmotive.com to request a quotation on this optional item.

PRODUCT PARTS

The SPECTRA TUNE LAB includes the following Hardware and Software items:

- **Spectrally tunable** LIGHT ENGINE & power adaptor
- LIGHT HUB & power adaptor
- Standard optical tables compatible mounting holes adaptors
- Communications cable
- End-of-line (EOL) device
- USB cable
- µWAVE Software©
- IP67 rugged carrying suitcase

OPTIONAL:

- C-mount adaptor
- RESTful API

Figure 8. SPECTRA TUNE LAB IP67 carrying suitcase

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DIMENSIONS (in mm)

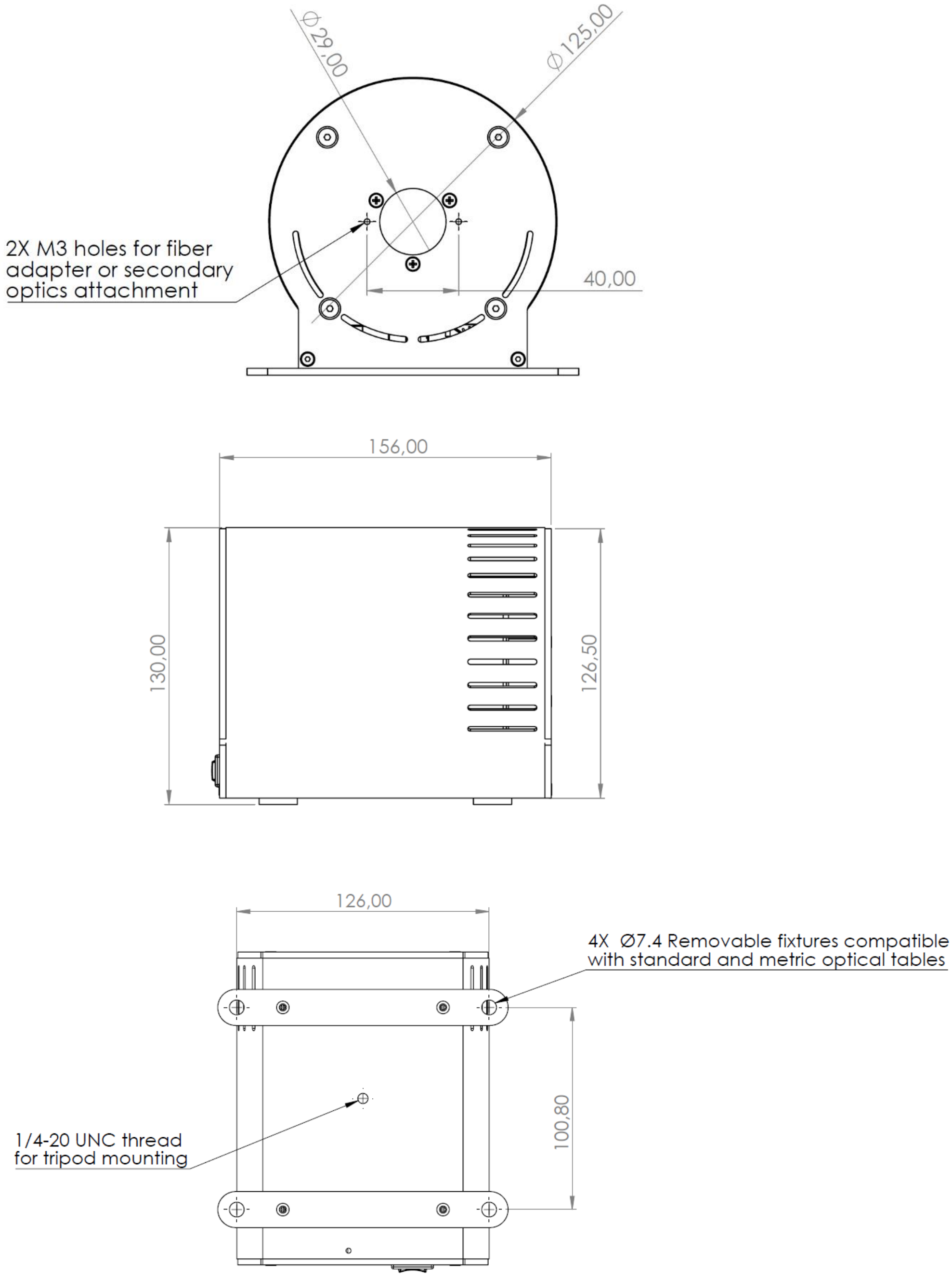

Figure 9. SPECTRA TUNE LAB dimensions

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OPTIONAL: C-MOUNT ADAPTOR

LEDMOTIVE can provide a C-mount adaptor to attach it to the SPECTRA TUNE LAB optical area.

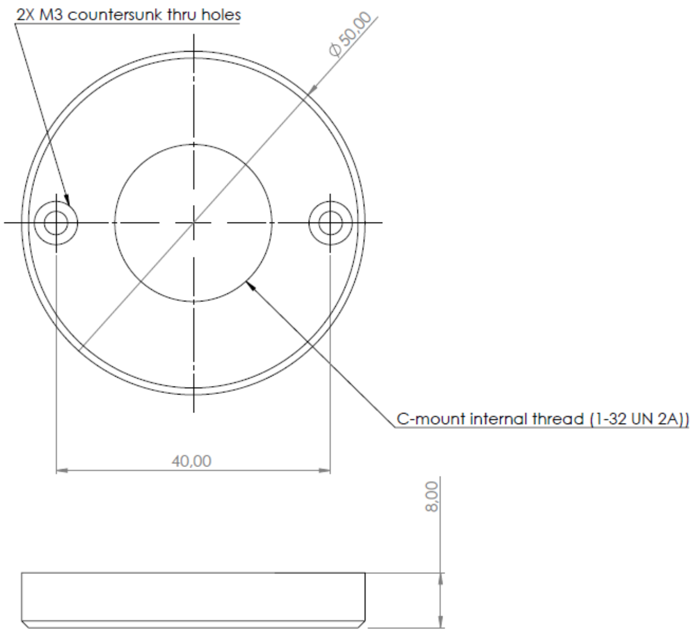

Figure 10. C-mount adaptor dimensions

C-mount is a market standard in optics. This C-mount adaptor is designed to allow the connection of compatible standard light guide connectors (Liquid Light Guide and/or Optic Fiber) to the SPECTRA TUNE LAB. Please contact our sales team at sales@ledmotive.com for further information.

QUICK START - OPERATING INSTRUCTIONS

1. Connect all the items together as shown below

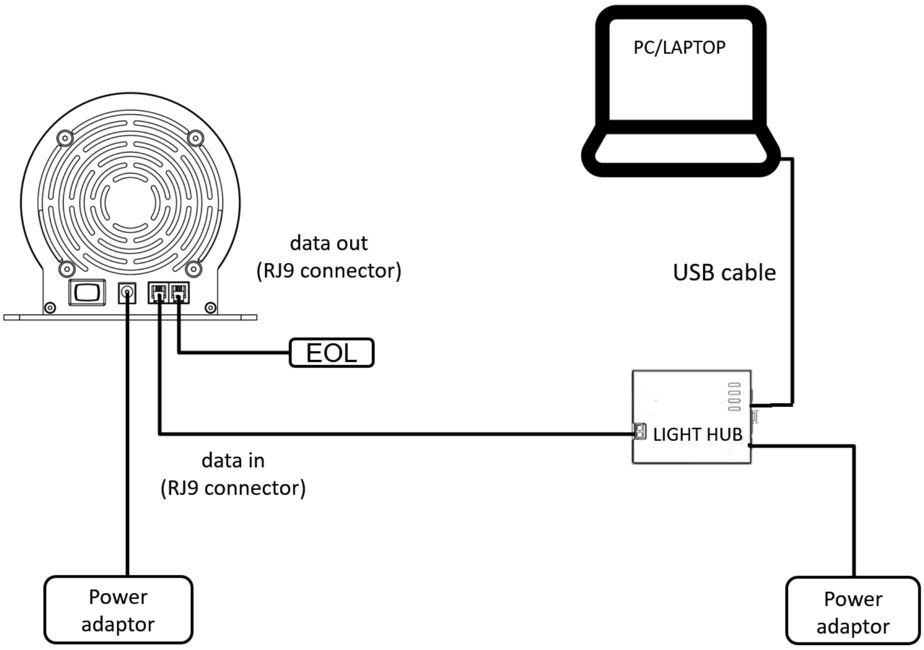

Figure 11. Schematics of the SPECTRA TUNE LAB connections. Instead of a USB cable, an ethernet cable can be used to connect a PC and the LIGHT HUB (not provided)

2. Make sure the End-Of-Line (EOL) is connected to the data out connector
3. Connect all power adaptors to the main electrical socket
4. TURN ON the device
5. Run the provided Control Software
6. Play and discover what you can do with the SPECTRA TUNE LAB

There may be cases when several SPECTRA TUNE LAB are being used together with the same LIGHT HUB. In this case it is possible to connect different devices in serial as show in *Figure 12* using the data in-data out connections.

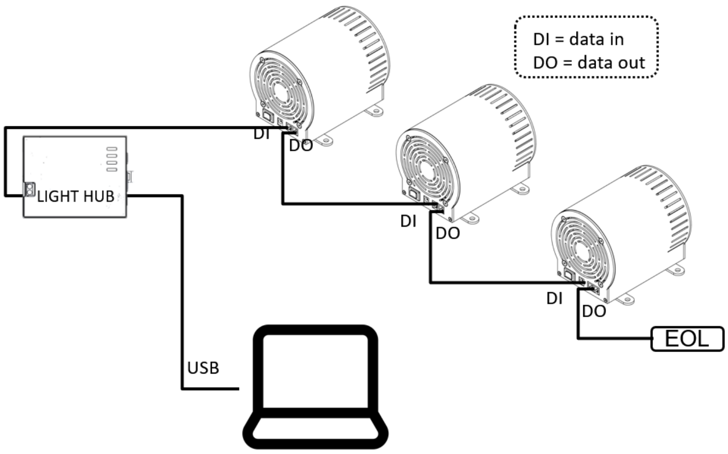

Figure 12. Schematics on how several SPECTRA TUNE LAB devices can be connected.

As part of a Customer Special Request, a Wi-Fi LIGHT HUB can be used to reduce the number of cables. Please contact our sales team at sales@ledmotive.com for further information.

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SPECTRA TUNE LAB
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FEATURES - SUMMARY

Source type	Multiple high-power LED
Output	10 different spectral bands
Max Radiometric Power	12.7 W (all channels at full power)[3]
Max Luminous Flux	3360 lumens
Spectral range	400-700 nm
Light output pattern	Lambertian
Operating temperature range	0 ºC to +35 ºC
Synchronous operation mode speed	250 milliseconds
Feedback control loop	Enabled by default
Nominal Input voltage	24 V DC (Constant voltage) ± 5%
Max Input current	3.3 A (limited by firmware)
Max Input electrical power	80 W (limited by firmware)
Communications protocol	bus EIA-485
Control software	Basic version
Dimensions (mm)	156 x 126 x 130
IP	20
Insolation Class	Class II
OPTIONAL	
Adapters	C-Mount adaptor
Advanced control software	RESTful API
Asynchronous operation mode speed	10 milliseconds (API required)

[3] Radiometric power may slightly change depending on the currently available LED binning

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SPECTRA TUNE LAB
Light Engine for Scientists

MAINTENANCE AND SERVICE

- If a fingerprint mark or dirt is observed at the diffuser, you may clean it. Before cleaning, disconnect from the main supply and allow the system to cool down. Wipe the surface of the diffuser gently with a tissue containing ethanol.
- Do not open, disassemble or manipulate the SPECTRA TUNE LAB system

WARNING AND SAFETY

- All necessary measures must be taken to avoid electric shock when handling electrical and/or electronic equipment. In case of doubt disconnect the main power supply when handling lighting equipment.
- The SPECTRA TUNE LAB is intended for use in dry interiors only. It is not water resistant and must be protected from adverse weather conditions (hot and humid).
- To avoid damage, do not expose it to spray, liquids, dust, or chemical products.
- This LED-based module must not be operated in explosive environments.
- To prevent injury, use this product in accordance with the International Standard "Photobiological Safety of Lamps & Lamp Systems" IEC 62471. This light engine falls under Risk Group RG1 – Low Risk Group in accordance to the standard IEC 62471:2008. Regardless of the risk factor classification, LEDMOTIVE does not recommend staring directly into any LED lamp or luminaire.
- During normal operation, the fixture can achieve high temperature, be careful when handling it to avoid burning.
- The SPECTRA TUNE LAB device uses an active cooling system to dissipate the heat produced by the LEDs when they are on. Do not manipulate the luminaire when it is connected to the mains and ensure there are always free space around the device to allow prevent any contact with the moving parts (cooling fan).
- All statements regarding safety of operation, warranty and technical data only apply when the unit is operated correctly according to its specifications. The safety of any system incorporating the equipment is the responsibility of the assembler of the system. This system must not be operated in explosive environments

DISPOSAL

- In accordance with EU Directive WEEE (Waste Electrical and Electronic Equipment), this scientific equipment must not be disposed of with another household waste.
- At the end of their life, it must be taken to the appropriate local facility available for the disposal or recycling of electronic products.

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Light Engine for Scientists

WARRANTY

- This product has passed the EU regulations and directives. See *Appendix 1* for further details. LEDMOTIVE offers a one-year limited warranty.

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SPECTRA TUNE LAB
Light Engine for Scientists

APPENDIX 1: Compliance with directives and norms

This product complies with the following directives and norms:

DIRECTIVES:

- 2014/35/EU: Low Voltage Directive (LV)
- 2014/30/EU: Electromagnetic Compatibility (EMC) Directive
- 2011/65/EU: RoHS Directive

NORMS:

- EN 61010-1:2010 Safety requirements for electrical equipment for measurement, control, and laboratory use.
- EN 62471:2008 Photobiological safety of lamps and lamp systems
- EN 50581:2012 Technical documentation for the assessment of electrical and electronic products with respect to the restriction of hazardous substances

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Light Engine for Scientists

APPENDIX 2: Light programmatic control with the RESTful API

To be able to control the lights, a RESTful API is available to send the proper commands to the SPECTRA TUNE LAB.

Once the LIGHT HUB is powered on and connected to a computer, it will start the REST API automatically and will begin to listen to a specific port.

With the API the user can:

- Read the temperature from the PCB Board
- Switch on the system with a default spectrum
- Send a specific spectrum
- Read a spectrum
- Read the current luminous flux of the system
- Switch off the lights
- Define a default spectrum
- Define parameters settings
- Work the luminaire in asynchronous mode
- And much more…

Ledmotive Technologies, SL
Jardins de les Dones de Negre 1, PL 2 - 08930 Sant Adrià de Besòs (BARCELONA) - SPAIN
EMAIL : info@ledmotive.com
TEL +34 934 884 890

B.2 The VEGA 07 datasheet

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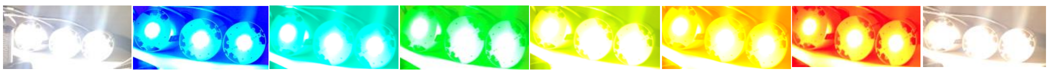
VEGA 07 SERIES

Multi Spectral Light Source



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VEGA 07 LED Module
Multi Spectral Light Source

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VEGA 07 LED Module
Multi Spectral Light Source

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VEGA 07 LED Module
Multi Spectral Light Source

DESCRIPTION

The VEGA 07 module is the most advanced light engine from LEDMOTIVE. It's built up with seven different colored (or channel) high output power LED to provide with a versatile multispectral light source in the visible range of the electromagnetic spectrum for smart lighting solutions. Light can be dimmed down to 5% of the full power for each color independently. The LED module can deliver either white light or any light spectrum from the modulation of each of its different channels separately. Being a standard LED technology no warm up time is required.

Embedded in the VEGA 07 module are the driver electronics for precise control of current, PWM and light output control, as well as an optical device for sensing purposes. A closed feedback loop allows for color matching with a target value and provides stability to avoid drifts in time due to thermal or ageing effects.

Figure 1. VEGA 07 side view

LED-BASED MODULE – Features

- High power multi-spectral LED module engine
- Built up with 7 different (colored) LED types
- Independent color channel dimming
- Precise, accurate and stable light emission
- Light emitting surface of 23mm
- Compact and light weight system
- No warm up required
- Optical feedback control with proprietary color science algorithms.
- Overheat temperature protection limit control.
- The default wired communication is based on a EIA-485 using the LEDMOTIVE LIGHT HUB© device
- Optional: Software tool to select the heat sink and analyze the thermal response.

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VEGA 07 LED Module
Multi Spectral Light Source

LED-CHANNELS

The VEGA 07 module contains seven LED channels for multispectral reproduction. The spectral output covers the wavelength range from 420 nm to 730 nm as shown in Table 1 and Figure 2.

Channel	Color	Peak Emission (nm)	Radiometric value (W)	Photometric value(lm)	FWHM (nm)
CH 1	Royal Blue	455	1.26	45.7	23
CH 2	Blue	480	1.08	123.4	27
CH 3	Cyan	505	1.18	409.1	34
CH 4	Green	535	0.64	363.7	37
CH 5	Lime	550	2.2	971.4	117
CH 6	PC Amber	595	2.53	907.6	81
CH 7	Red	640	0.95	151.5	20

Table 1. LED channel physical description

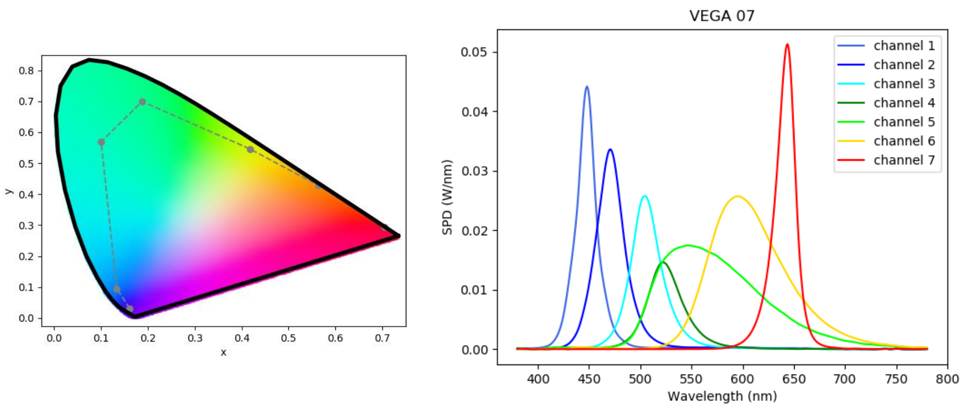

Figure 2. (left) CIE 1931 xy coordinates of the 7 channels that define the color gamut and (right) Spectral Power Distributions (SPDs) of each LED channel

Since the light output of the VEGA 07 module is generated by mixing 7 wavelength (color) channels, every spectrum is determined by 7 independent PWM signals. Consequently, the luminous flux is not constant across the 1931 CIE diagram. All active channels are mixed, providing with a smooth (uniform in color) light with a Lambertian pattern profile

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SPECTRAL MODULATION

Product performance based on two different spectral modulations that reproduce a blackbody radiation curve at two different temperatures (2700 K and 6500 K) with a high CRI(Ra) value is shown in Figure 3:

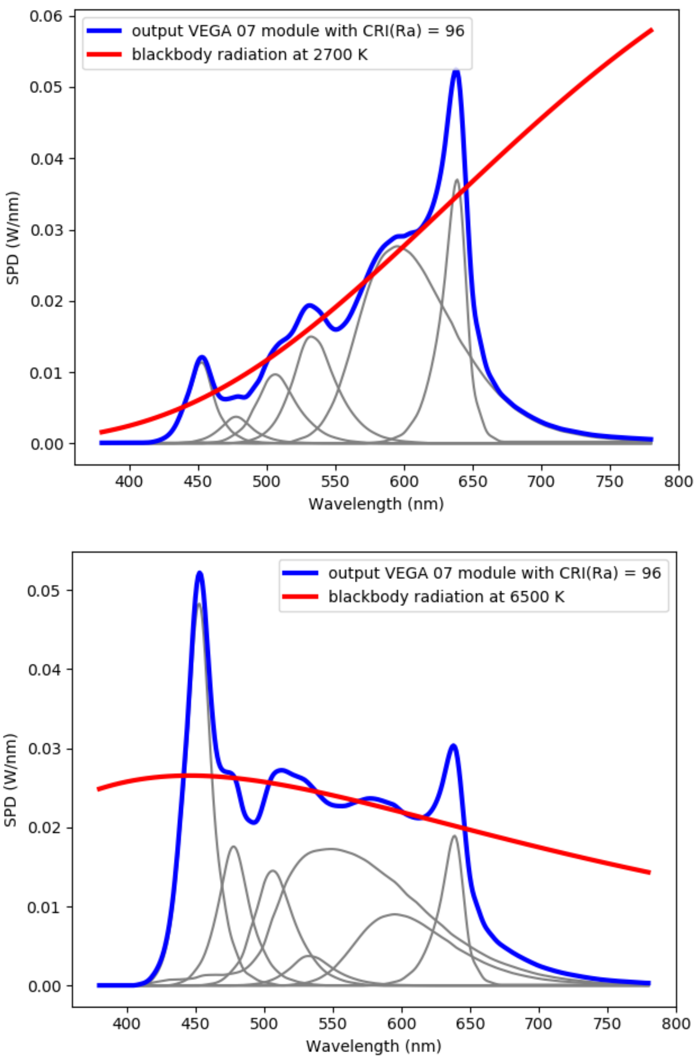

Figure 3. Example of two different spectral fittings (2700 K and 6500 K blackbody radiation)

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COLORIMETRIC RESULTS: COLOR MATCHING and STABILITY OVER TIME

The typical color matching and stability is shown in Figure 4 and is based on a variety of different Correlated Color Temperatures (CCTs). The typical colorimetric response with the optical feedback loop enabled is Duv'< 5x10^{-3}. All results are within the 2nd step Mac Adam ellipse from the ANSI C78.377-2015 specifications.

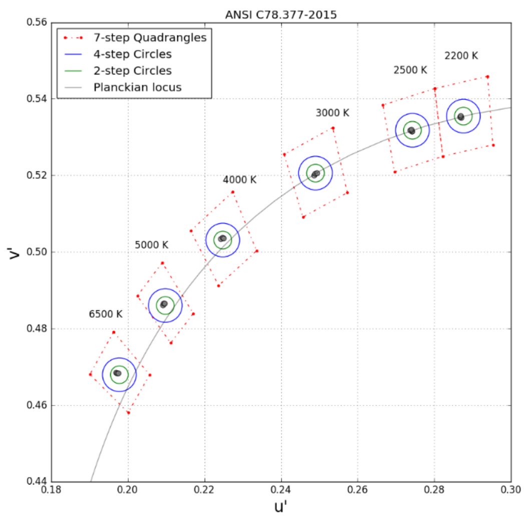
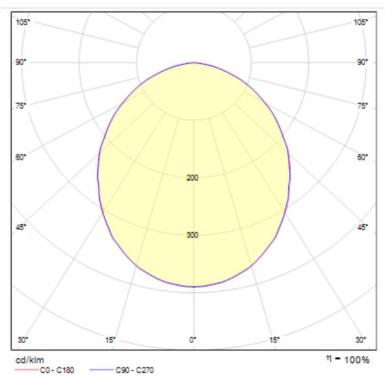


Figure 4. Color Matching and Stability response. Tolerance of ±0.005 on x and y coordinates in the CIE 1931 color space

PHOTOMETRIC DATA



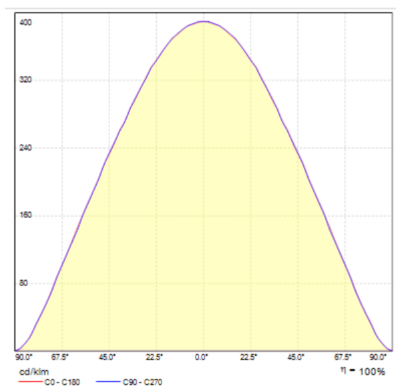


Figure 5. Light distribution

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ELECTRICAL SPECIFICATIONS

Nominal Input Voltage	24 V DC (Constant Voltage) ±5%
Max. Power Input	80 W (limited by firmware)
Max. Current Input	3.3 A* (limited by firmware)
Power and data connector	MOLEX 43025-0409
Data communication (A, B) control	LEDMOTIVE proprietary protocol**

* fuse protection at 4.0 A
** based on a communication bus EIA-485 (also known as RS-485)

Table 2. Electrical specifications

Figure 6 shows the schematics of the VEGA 07 module displaying its different types of connectors and wiring connections. The 12 V denotes a fan power output, a 24V denotes an external power supply output and the A, B denotes the control communication signal entry points.

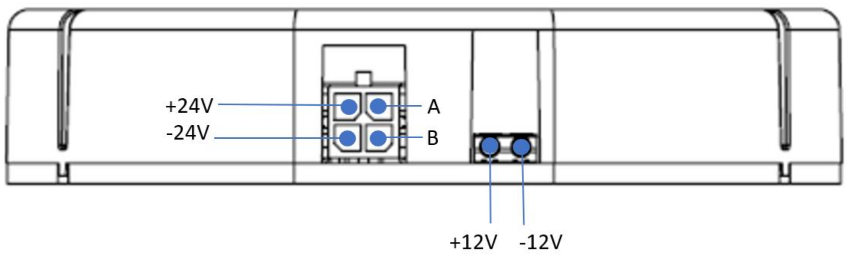

Figure 6. Wiring Schematics

The module includes a fan power connector in case an active cooling fan is attached to a heat sink and the LED module

Fan output voltage	12 V DC (Constant Voltage)
Fan power connector	MOLEX 104238-0210
Max fan output current	100 mA***

*** resettable fuse at 25ºC

Table 3. fan connector details

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MECHANICAL DIMENSIONS

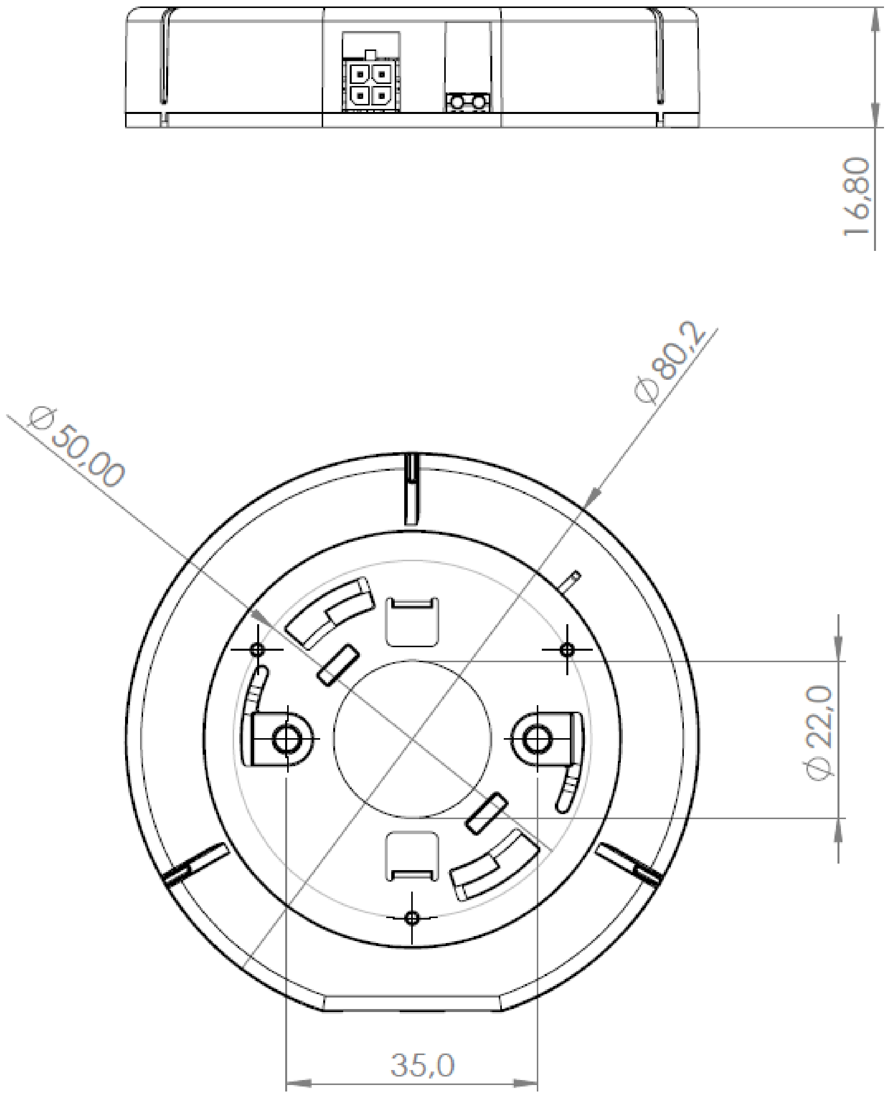

Figure 7. All dimensions are in millimeters (mm)

THERMAL MANAGMENT

A cooling component is needed to dissipate the heat away from the base of the VEGA 07 module. Either a passive heat sink or an active cooling with a fan can be used depending on a fixture size restriction. Active cooling is generally smaller but has moving parts while passive cooling is bigger and heavier.

VEGA 07 generates a maximum of 45 thermal power (W). The maximum temperature in the check point is indicated in Figure 8 and should not be higher than 80 °C

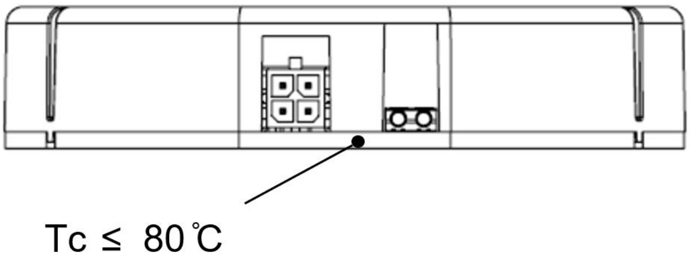

Figure 8. Thermal check point

HEAT SINK MOUNTING INTERFACE

The mounting holes for the heat sink are according to the Zhaga standard (book 10) with two holes 35 mm apart, as shown in Figure 9. Based on the current experience LEDMOTIVE recommends using heat sinks with thermal resistance < 0.5C/W.

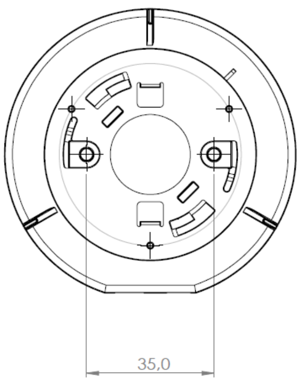

Figure 9. Mounting holes for the heat sink

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HEAT SINK DIMENSIONING

In order to maximize the luminous flux, a proper heat sink needs to be selected accordingly.

As a reference value, testing* has been carried out to provide a reference value. A heat sink with a heat resistance of Rhs≤1.2C/W* should be used. It is recommended to use thermal interface material between the module and the selected heat sink to reduce the thermal impedance. The heat dissipation is dependent of many variables such as the desired output spectrum, the dimming level, the luminaire design, the location of the luminaire in the ceiling, etc. Therefore, is it highly recommended to perform a test at least in the final luminaire configuration.

A specific software to check the thermal behavior has been developed and it's available under request.

* performed at ambient temperature of 25°C, with a 4000K spectrum at CRI>95, using a thermal compound of 2.9W/mK between the module and the heat sink.

PCB THERMAL PROTECTION

The VEGA 07 module incorporates an automatic temperature check and control algorithm for protection. This protection control** is enabled by default from the factory. In an unlikely event of PCB overheating (fan or dissipation failure, poor heat dissipation due to wrong dimensioning, harsh environments, etc.), the VEGA 07 will automatically reduce its luminous flux and consequently its consumed electrical power to keep the temperature within a safety range and to protect its components. In this way, the optimal working conditions that warrant the lifespan of the LED engine and its components are always preserved.

** when PCB temperature raises over 80°C

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FEATURES - SUMMARY

Source type	Multiple high-power LED
Output	7 different spectral bands
Max Radiometric Power	9.7 W (all channels at full power)1
Max Luminous Flux	2800 lumens
Spectral range	420-730 nm
Light output pattern	Lambertian
Operating temperature range	0 ºC to +35 ºC
Synchronous operation mode speed	250 milliseconds
Feedback control loop	Enabled by default
Nominal Input voltage	24 V DC (Constant voltage) ± 5%
Max Input current	3.3 A (limited by firmware)
Max Input electrical power	80 W (limited by firmware)
Communications protocol	bus EIA-485
Dimensions (mm)	Ø82.5 x 16.6 mm
IP	20
Insolation Class	Class II

[1] Radiometric power may change depending on the available LED binning

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VEGA 07 LED Module
Multi Spectral Light Source

MAINTENANCE AND SERVICE

- Do not open, disassemble or manipulate the VEGA 07 LED-based module.
- If a fingerprint mark or dirt is observed at the diffuser, you may clean it. Before cleaning, disconnect from the main supply and allow the system to cool down. Wipe the surface of the diffuser gently with a tissue containing ethanol.
- No user serviceable parts inside. Replacement of the entire VEGA07 is required when malfunction may occur.

WARNING AND SAFETY

- Before installing, servicing, or performing routine maintenance upon this product, follow the general precautions.
- ALWAYS adhere to safety instructions and warnings
- All necessary measures must be taken to avoid electric shock when handling electrical and/or electronic equipment. In case of doubt disconnect the main power supply when handling lighting equipment.
- All statements regarding safety of operation, warranty and technical data only apply when the unit is operated correctly according to its specifications. The safety of any system incorporating the equipment is the responsibility of the assembler of the system.
- The VEGA 07 is intended for use in dry interiors only. It is not water resistant and must be protected from adverse weather conditions (hot and humid).
- Keep away from flammable materials. To avoid damage, do not expose it to spray, liquids, dust or chemical products.
- Do not cover the optical output of the VEGA 07 with an adherent film.
- Do not stare directly into the LED Light source at short distance or long-exposures
- Ensure that heat sink fins and/or fans are not obstructed.
- During normal operation, the fixture can achieve high temperature, be careful when handling it to avoid skin burning.
- Do not operate the VEGA 07 with missing or damaged components.

ENVIRONMENTAL AND DISPOSAL COMPLIANCE

- LEDMOTIVE is committed to provide environmentally friendly products to the solid-state lighting market. VEGA 07 is compliant to the European Union directives on the restriction of hazardous substances in electronic equipment, namely the RoHS Directive 2011/65/EU and REACH Regulation (EC) 1907/2006.
- LEDMOTIVE will not intentionally add the following restricted materials to its products: lead mercury, cadmium, hexavalent chromium, polybrominated biphenyls (PBB) or polybrominated diphenyl ethers (PBDE).

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- In accordance with EU Directive WEEE (Waste Electrical and Electronic Equipment), LED modules must not be disposed of with another household waste.
- At the end of their life, it must be taken to the appropriate local facility available for the disposal or recycling of the electronic parts.

WARRANTY

- This product has passed the proper EU regulations and directives.
- LEDMOTIVE offers a five-year limited warranty

Ledmotive Technologies, SL
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EMAIL : info@ledmotive.com
TEL +34 934 884 890

Appendix C

The design and optical development of an industrial light engine

This appendix includes some of the improvements to the VEGA 07 compared with earlier prototypes. The improvements were aimed at cutting costs, reducing its size, and enhancing the ease of assembly. A detailed description of the optical characterization is included, as well as a brief description of the calibration control unit that was designed to be deployed in production.

In the SPECTRA TUNE LAB core light engine, a large number of individual parts were required for assembly, namely the metallic enclosure, driver PCB, control PCB, LED PCB, light guide, enclosure lid, mixing chamber, diffuser, and diffuser holder. All these parts would be assembled together as shown in Fig. C.1 on the left.

The VEGA 07 was designed to have a small number of parts and an easier assembly process, that is, one PCB for drivers and for the LEDs, one control PCB, a plastic enclosure, a mixing chamber, a diffuser, and the holder. The individual parts are shown in Fig. C.1 on the right.

In the new design, four of the seven threaded joints were removed, and the three remaining joints became clipping joints or adhesive joints, which made the jointing less time-consuming. The overall assembly process of the light engine was made simpler because there was no light guide (it was very delicate and had to be handled very carefully); thermal paste was no longer used (it was used between the PCB and the aluminium enclosure); and the design used a colour sensor instead of a spectrometer (a larger and considerably more delicate device). The light engine can now be assembled in four easy steps, as shown in Fig. C.2). The height and

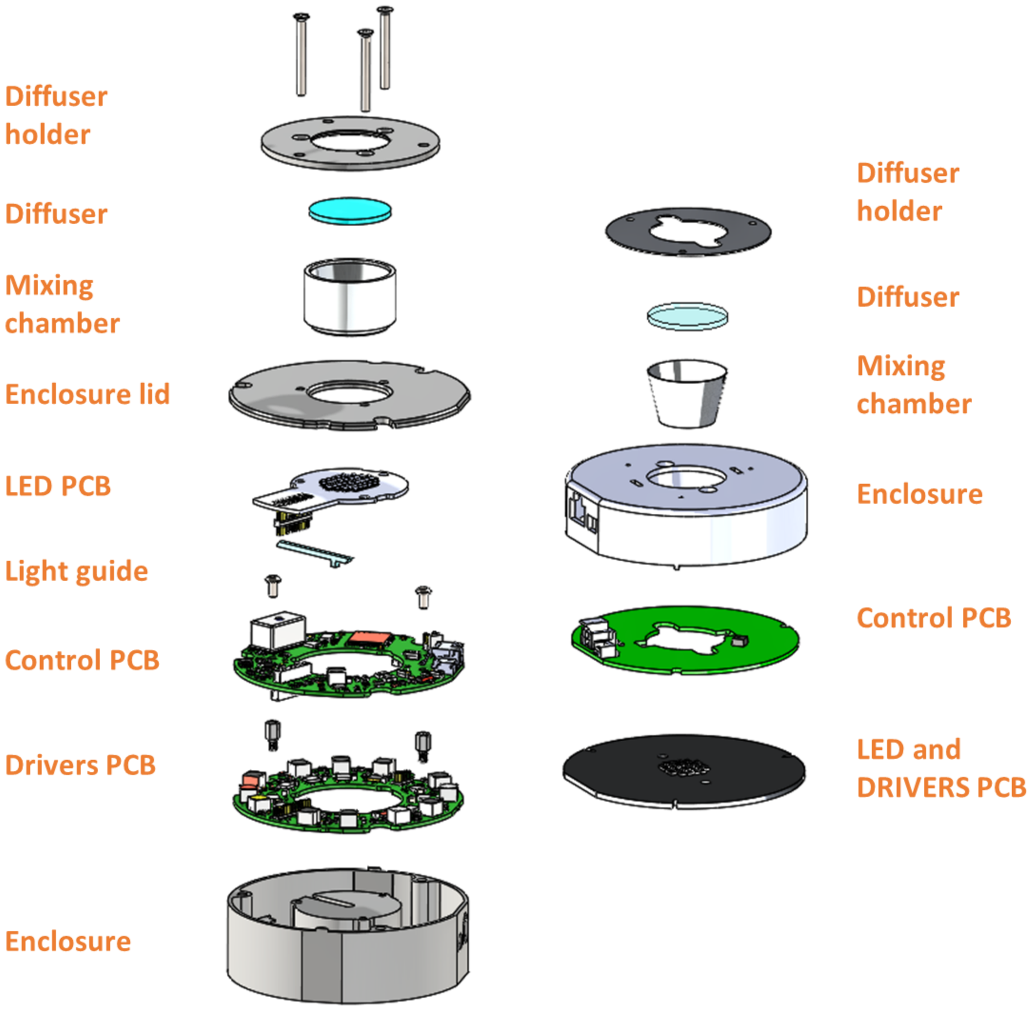

Figure C.1: (left) Mechanical design for the SPECTRA TUNE LAB core light engine. (right) New mechanical design for the VEGA 07 light engine.

diameter of the device were previously 0.049.6 m and 0.088 m, respectively and in the new design they are 0.0166 m and 0.082 m, respectively. Fig. C.3 and Fig. C.4 show pictures taken from different angles of the final VEGA 07 light engine.

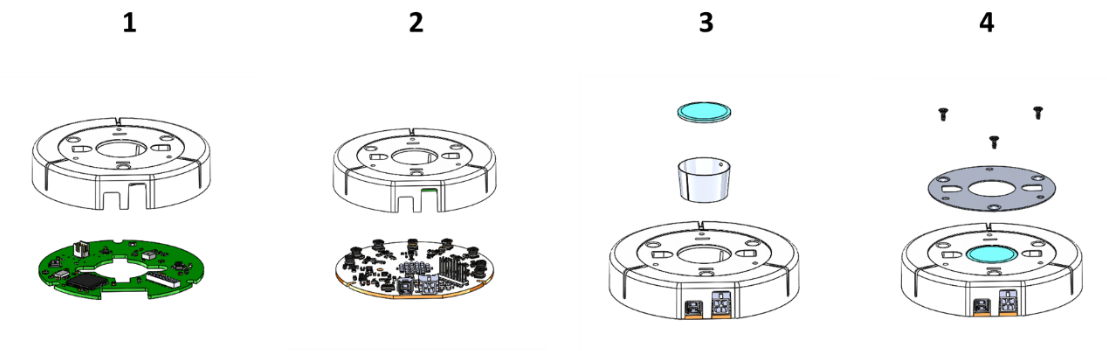

Figure C.2: VEGA 07 assembly process.

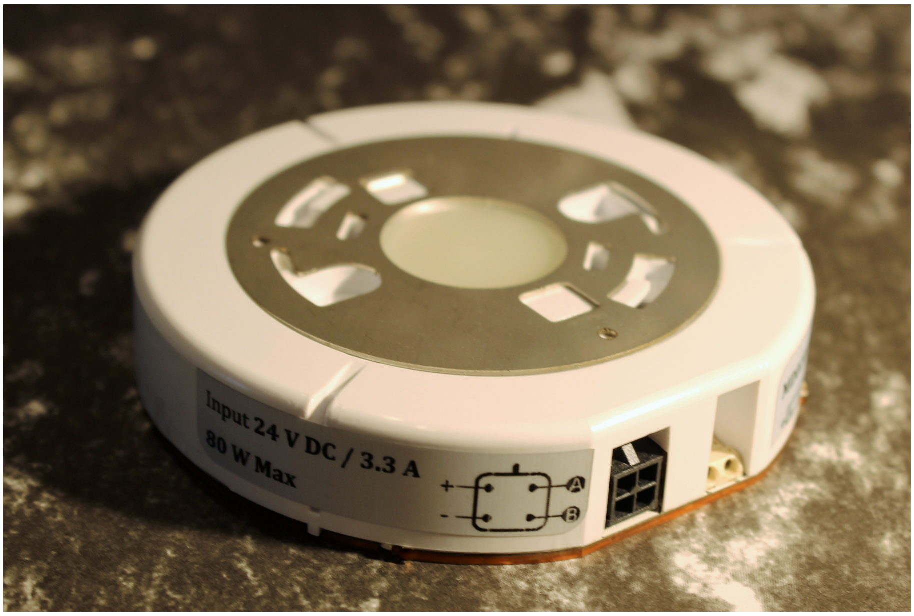

Figure C.3: Picture of the VEGA 07 light engine.

A set of temperature sensors inside the light engine monitors temperature. Several parameters may not exceed the prescribed values, and continuous monitoring is required. The controller is a PID and it is designed to be guided by the temperature of the LED PCB. It is not always activated; however, it always controls the PWMs of all the channels and monitors the temperature values to prevent the temperature from exceeding the threshold value, which could compromise the functioning of the device.

Fig. C.5 shows how the controller works i.e. when the threshold values are set to 58 °C, the LEDs PWMs are adjusted in power until the temperature values are

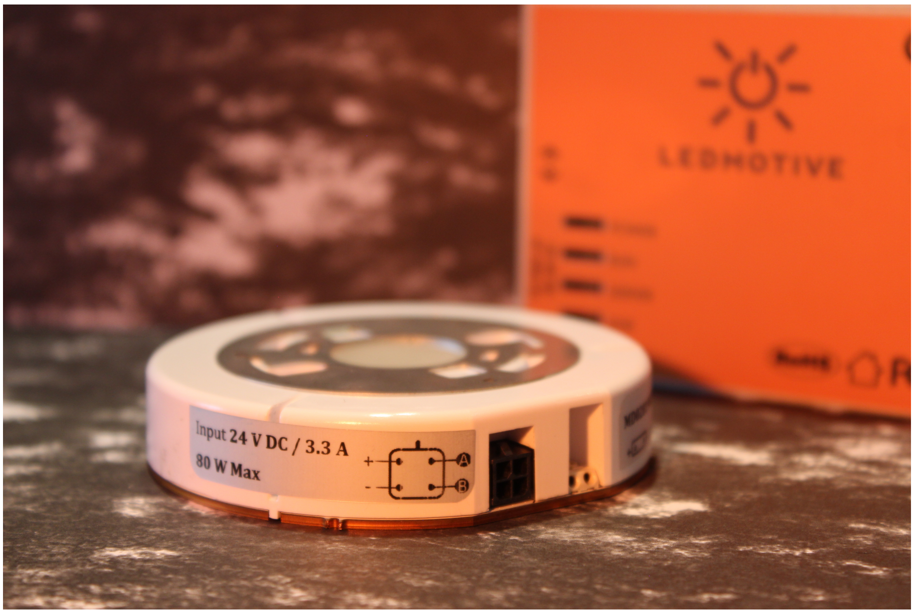

Figure C.4: Picture of the VEGA 07 light engine.

stable and do not surpass the limit (without modifying the SPD shape or colour of the emitted light). When the threshold is changed to 68 °C, the PID automatically allows the LED channel PWMs to emit power so that they can reach the desirable temperatures of the new threshold value set.

In production, each light engine is calibrated and optically checked extensively as shown in Fig. C.6.

The calibration entails individually tuning each LED channel and measuring the SPDs with a spectrometer (a fibre plugged to an integrating sphere). A comparison of the SPD values measured to selected threshold values for each channel (optical power and wavelength limits) is conducted. This to ensure that the bins and LEDs are correctly assembled. In addition, the temperature sensors are inspected and the colour sensor is calibrated with the same LEDs generating a set of standard and known CCTs (2000 K, 3000 K, 4000 K, 5000 K, 6000 K, 7000 K, 8000 K). A dedicated algorithm calibrates the XYZ output of the colorimeter to what it is expected for each of the selected CCTs.

During the calibration process the following tasks are to be performed:

1. Check the assembly of the PCBs: designed to test if there were some problems during assembly.
2. Check the communications circuit: check if the communications path is correct and signals are sent and received.

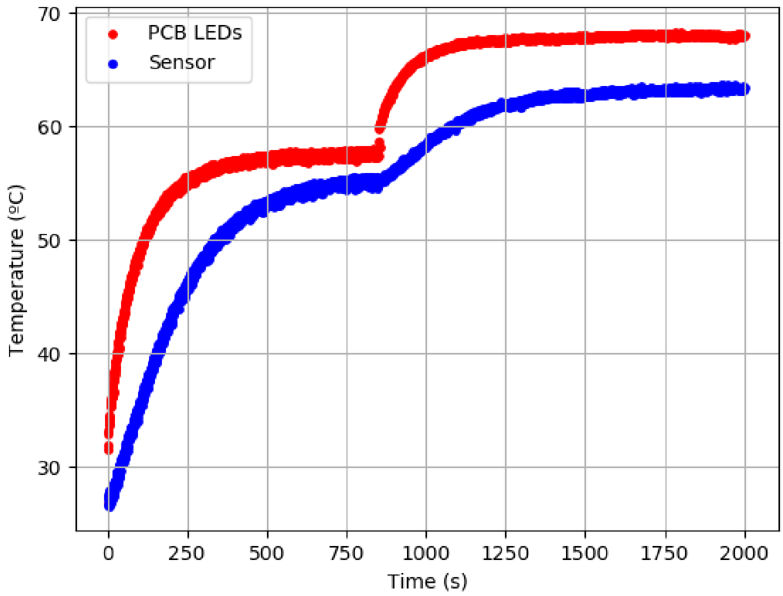

Figure C.5: PID temperature control. In this example, the temperature threshold value was set to 58 °C and after 800 seconds it was changed to 68 °C for the sake of showing how the system behaves. The red line are the temperature values in the LEDs PCB and the blue line are the temperature values from the sensor location.

3. Check the temperature sensors.
4. Calibrate the power sensors.
5. Measure and store the LEDs SPD pre-sets in the flash memory.
6. Calibrate the optical sensor.

Fig. C.7 shows the different LED channels at different optical powers. We test the linearity of each PWM and compare it with the lumens emitted. Fig. C.8 shows that each channel PWM has a linear relation with the optical power.

Fig. C.9 shows the colours of each LED channel individually and Fig. C.10 shows a warm, a neutral and a cool CCT created with the VEGA 07 light engine. Finally, Fig. C.11 shows different colours created with a set of light engines in a real office installation done in London.

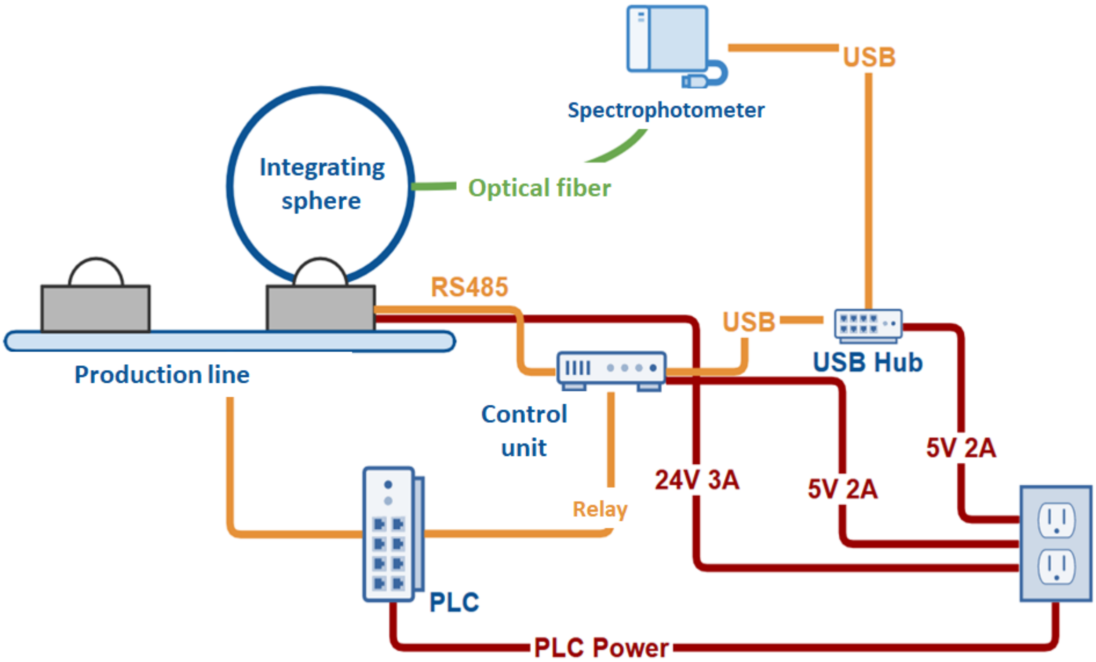

Figure C.6: Schematic of the calibration process done in production.

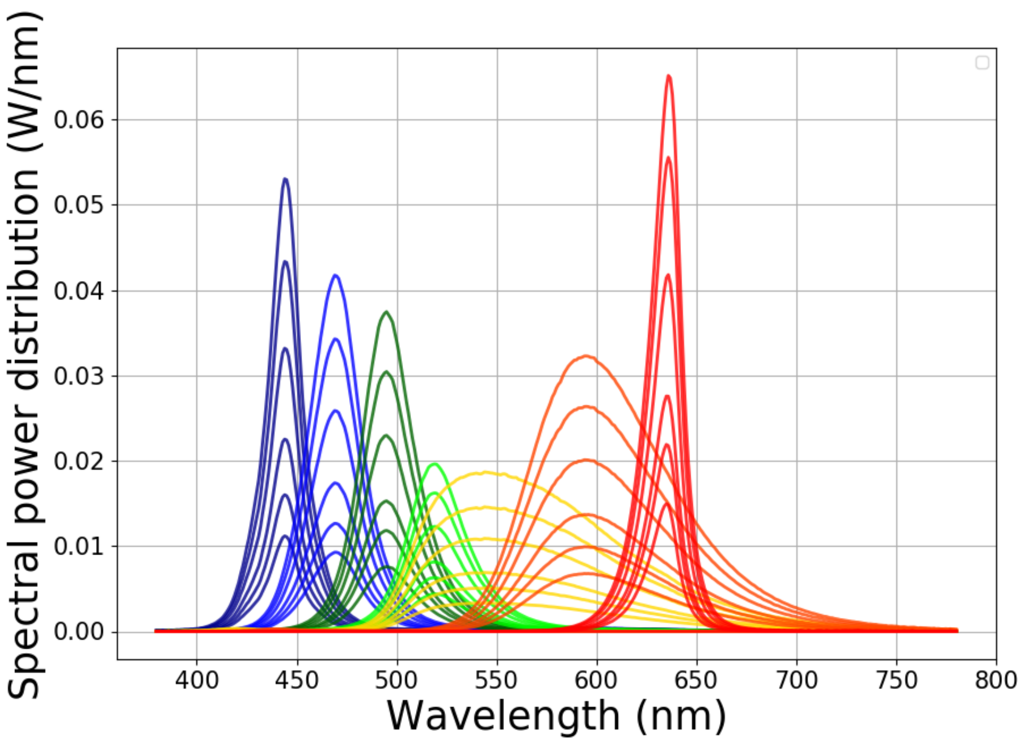

Figure C.7: The 7 LED channels at different optical powers.

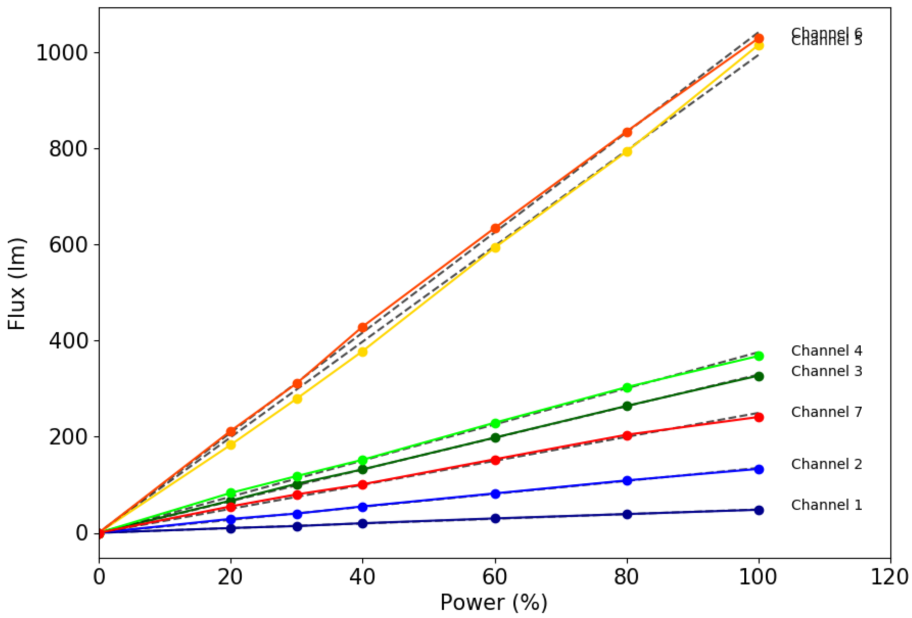

Figure C.8: The linear relation between PWM and optical power for each LED channel.

Figure C.9: The VEGA 07 light engine showing the colours of each LED channel.

Figure C.10: Three different CCTs made with the VEGA 07 light engine.

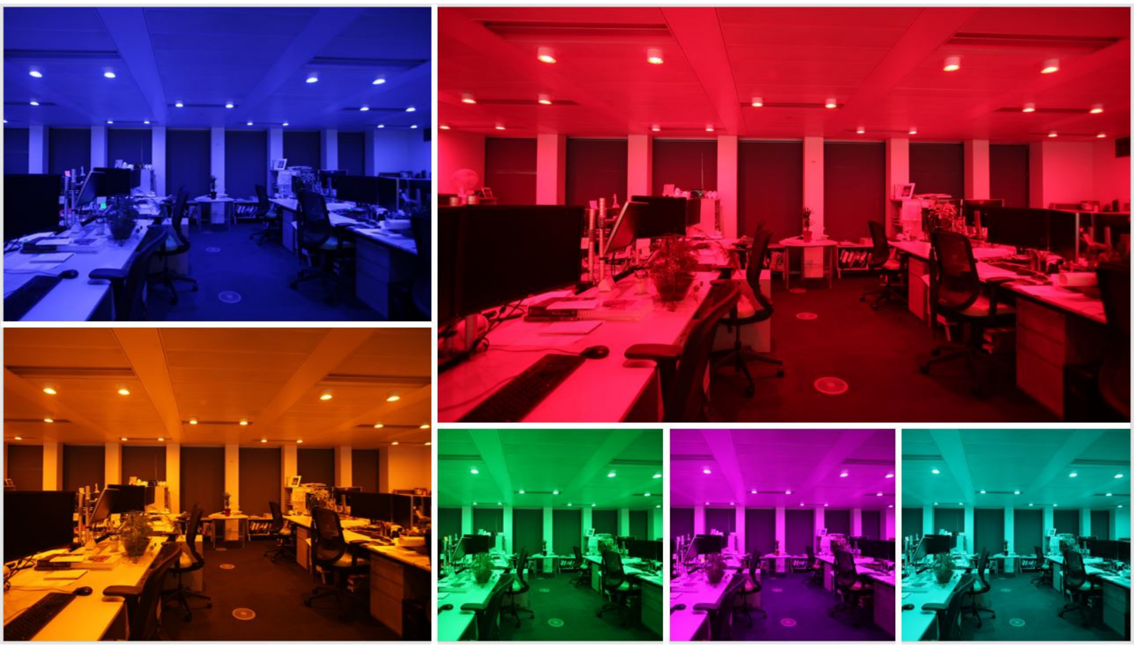

Figure C.11: Colours created with the VEGA 07 light engine in an office installation done in London, United Kingdom.

Appendix D

Real-time daylight matching using spectrally tunable systems: a natural circadian strategy for indoor lighting

This appendix includes a detailed description of the set-up and the results of a system at ARUP's offices in London that we installed in spring 2019.

D.1 Introduction

Typical lighting installations in offices and buildings use static artificial sources that do not consider the spectral properties of light or daylight changes happening outdoors. However, it is now recognised that spectral variations in light elicit non-visual effects, including on emotion and cognition, and being exposed to natural daylight is positive for our health and well-being.

Previous works that aimed to bring real daylight spectral properties indoors without windows used optical fibers or lenses to collimate the light [61]. Although possible, the solutions proposed are extremely expensive and unfeasible technically in most buildings without changing the whole constructed structure.

In this work, we made use of our advanced spectrally tunable light engines to copy, in real-time, the daylight spectra arriving at a spectrometer placed on the roof of an office building, transferring the smooth changes in illumination and wavelength components inside as they are measured outdoors.

This approach is radically different from that offered by traditional lighting systems where light fixtures have a static spectrum and illuminance, totally unaware of what is going on outside. Furthermore, our method follows a circadian lighting strategy for human-centric lighting applications, where lighting design supports the human diurnal need for illumination and darkness cycles to reset the circadian system [48]. Circadian lighting should consider the changes in spectrum of light over the course of a day, and those changes happen in the very specific latitude and longitude where people live.

All in all, our aim in this work was to design, develop and test in a real office setting a novel circadian strategy for indoor lighting based on spectral fidelity to daylight. In the next lines we explain the methodology followed, describe the set-up used and compare the light properties inside and outside. Finally, we will discuss the anonymous comments made from office workers when they were exposed to only fluorescent lamps and when they worked unknowingly under the real-time daylight matching system.

D.2 Set-up

A total of 36 LEDMOTIVE (model VEGA 07, see B.2) tuneable downlights were used for this experiment. They were mounted onto the ceiling of the lighting team section in ARUP's offices in London, the United Kingdom.

An Ocean Optics spectrometer with a cosine corrector placed on the roof the building was used to measure daylight. The device was controlled by a Python 3.5 script executed in a Raspberry Pi computer (see Fig. D.1). It read the spectrum every few seconds and sent the data to an Amazon Web Service (AWS) server located on a cloud, that also served as a database for storing all the information generated. The spectrometer was placed on top of a long mast with a clear view of the sky and with no obstacles around it (see Fig. D.2).

Fig. D.3 shows a full schematic of the system. When the cloud server receives new spectral data, it pushes the information to the Ledmotive's LightHub. This IoT smart bridge is located inside the building and controls the lighting system. The LightHub receives the spectral data (SPD and illuminance values collected from outside) and calculates in real-time the channel weights that result in the best spectral fitting to the target SPD. This is done using advanced heuristic algorithms that make sure that the final SPD is well fitted to the target SPD while also preserving its colour properties [51] [52]. Finally, the illuminance values measured outside are translated and adapted inside by using a proportional factor. The information is

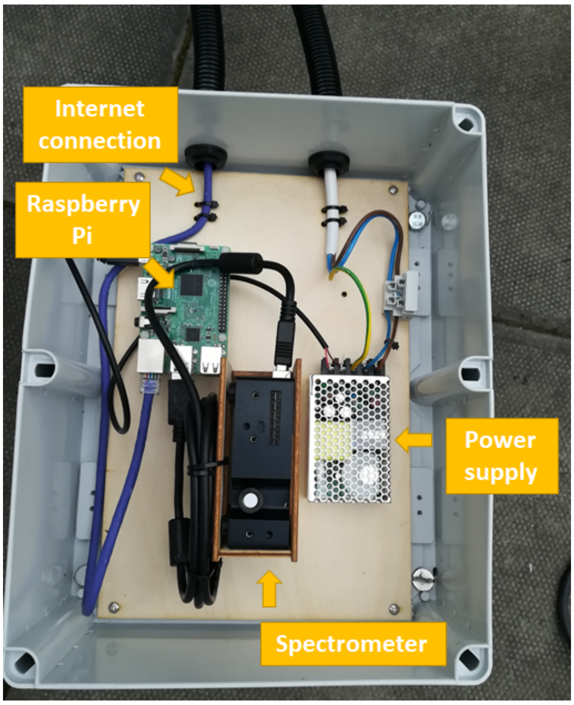

Figure D.1: Picture of the set-up used: an Ocean Optics spectrometer connected to a Raspberry Pi computer through a USB cable. The two cables entering the box are for electrical power and Internet connection.

Figure D.2: The spectrometer on top of a long mast in the roof of the building, with a clear view of the sky and no near-by obstacles around.

sent to the light engines and any change in spectra and CCT measured outside is smoothly mimicked inside the office with a time lag lower than twenty seconds.

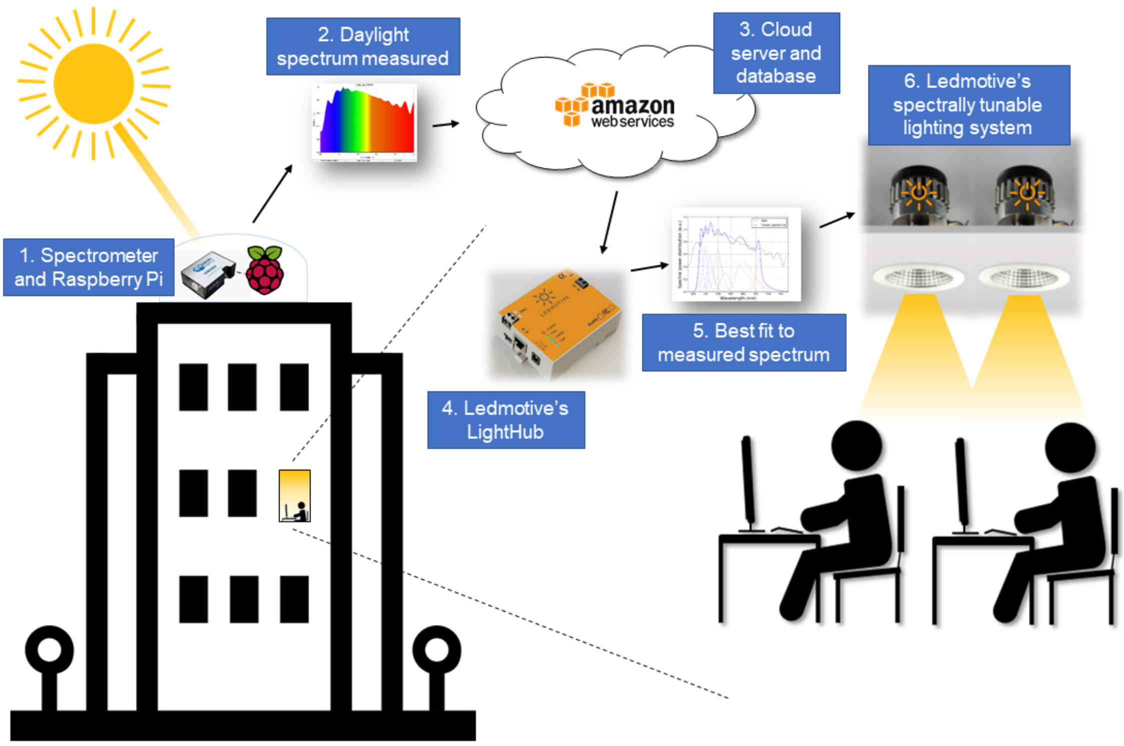

Figure D.3: Schematic of the setup: A Raspberry Pi computer controls the spectrometer placed in the roof (1) measuring daylight spectra (2). The information is sent to a cloud server (3), stored a database and pushed back to the Ledmotive's LightHub (4). The device, located inside the office, finds the best match to the target spectrum and illuminance (5) and sends the channel weights to the lighting system (6).

In the office, an area of approximately 160 m2 was selected, comprising the working desks of 15 people. The employees (age range 25 – 57; 6 males) have diverse roles within the company and volunteered to take part in the study. They were not informed of the different light conditions to be investigated or the expected outcomes. External light sources were blocked completely by covering the windows along one wall and inserting a screen between the study area and the adjacent working area.

First, they were exposed for two weeks to only commercial fluorescent lights (CCT of 3550 K, illuminance of 350 lx at desk level and CRI Ra of 80) and later, the real-time daylight matching set-up was installed and tested for another two weeks. Each Friday we asked and collected anonymous comments from workers to assess their impressions.

D.3 Results

A comparison of the daylight SPD to the SPD generated by the spectrally tuneable lighting system at different times of the day is shown in Fig. D.4. The sun's altitude, as well as clouds, fog, pollution, humidity and other meteorological factors, may affect the absorption of some specific wavelengths, modifying the SPD of sunlight until reaching the office space.

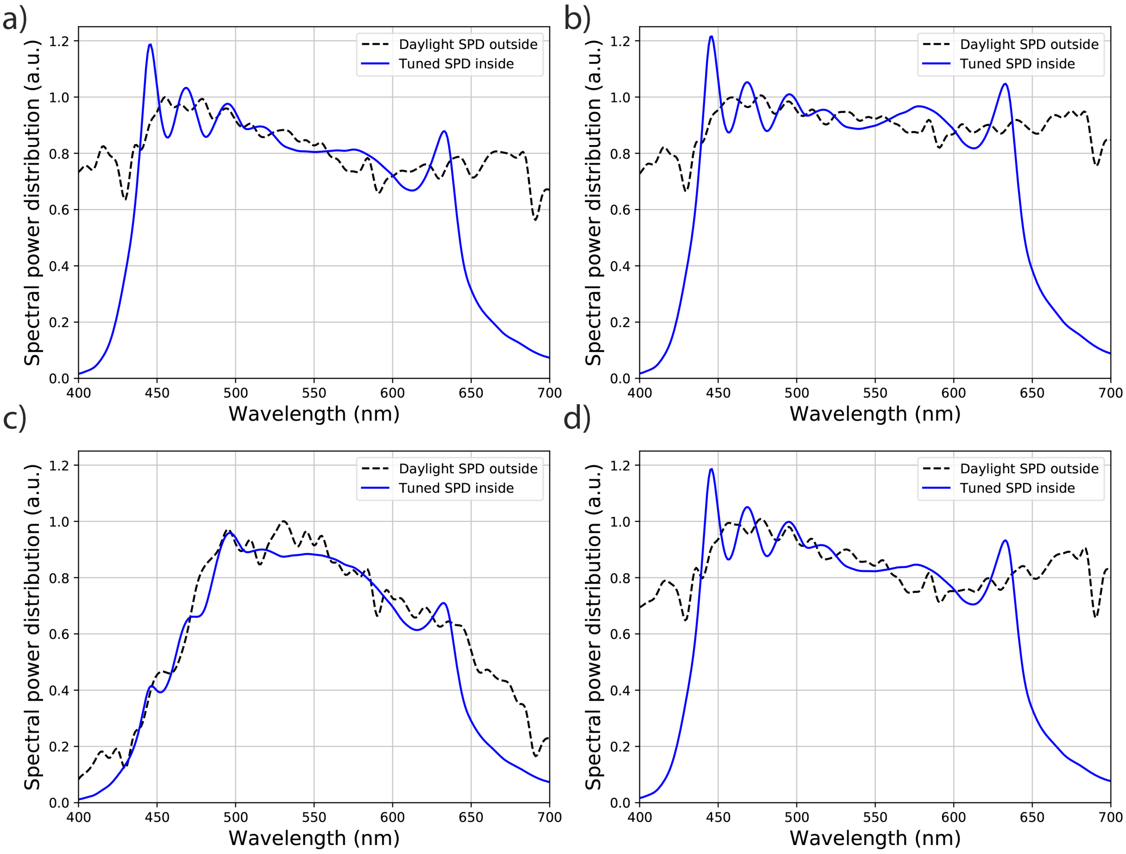

Figure D.4: Daylight SPD outside compared with the tunable lighting system SPD inside at different times of the day: 8 am (a), 10 am (b), 2 pm (c), and 6 pm (d).

The spectral fidelity between different light sources was assessed using the MAPD percentage (Eq. 1.1) and the results are shown in Table D.1. Using it as an indicator, the results show that the SPD of the fluorescent lamp reached an 85% error in comparison to daylight at 10 am. Similarly, the RGB light sources reach 65% and a commercial tuneable-white solution has a MAPD error of approximately 32%. The system we developed took into account the spectral shape of daylight at every iteration and rendered the best possible match with the number of colour channels that were available and the MAPD error was reduced to 10% at 8 am and at 10 am, 6% at 2 pm and 9% at 6 pm.

For comparative purposes Fig. 1.7 shows the fluorescent lamp, Fig. 1.8 shows the RGB light source, Fig. 1.9 shows the tuneable-white, and Fig. D.4 shows the spectrally tuneable system.

Test light source	MAPD
Fluorescent lamp	85
RGB light	65
Tunable-white	32
Tunable lighting system at 8 am	10
Tunable lighting system at 10 am	10
Tunable lighting system at 2 pm	6
Tunable lighting system at 6 pm	9

Table D.1: MAPD percentage between the target (daylight) and the different light sources emitted SPD. The fluorescent lamp, RGB and tunable-white sources are compared to daylight at 10 am. The Ledmotive's spectrally tunable lighting system is compared at different times of the day: at 8 am, 10 am, 2 pm and 6 pm.

Fig. D.5 and Fig. D.6 show the evolution of daylight on a full working day (April 9th 2019) compared to the indoor lighting system emission measured at desk level. Fig. D.5 shows the changes of CCT during the day and the maximum was at 8 am i.e. 6250 K and the minimum at 4 pm i.e. 5250 K. The changes were within a range of 1000 K. The difference between the outdoors and indoor measurements (inside the office at the desk level) were less than 50 K. The colour rendering index CRI Ra (see Fig. D.6) remained above 95 for natural daylight at all times and above 90 for the lighting system.

Fig. D.7 shows the illuminance measured indoors and outdoors on a day that was very foggy and cloudy in the morning with some raindrops and had a sunnier afternoon with a clear sky. The variable weather resulted in low lux values during the first hours of the day in comparison to the high illuminance values after 2 pm. In our approach, we translated the illuminance values from outdoors to indoors by adjusting the intensity using a proportionality factor and setting some limits for the comfort of the workers. The illuminance values were maintained between 300 lx and 500 lx at desk level.

The fluorescent lights and the spectrally tuneable lights were tested for two weeks each and we collected anonymous comments from participants to compare the different experiences. Fig. D.8 shows an image of the office following the fitting of the spectrally tuneable lights installed.

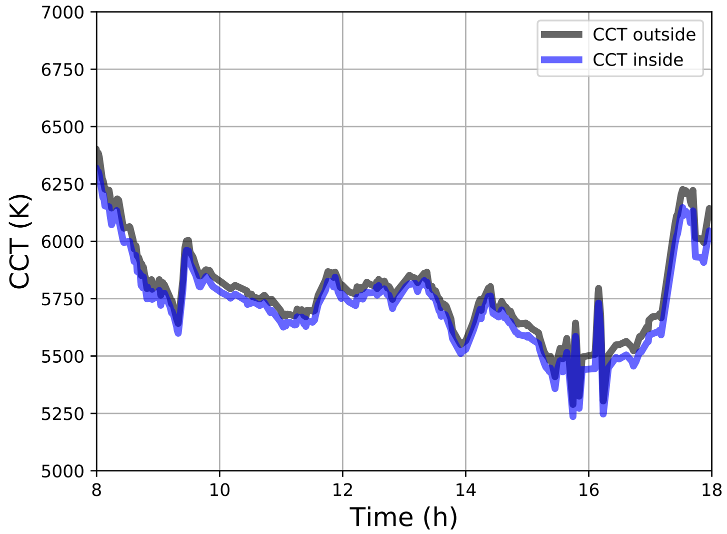

Figure D.5: CCT comparison between measured daylight outside (black lines) and measured light inside at desk level (blue lines).

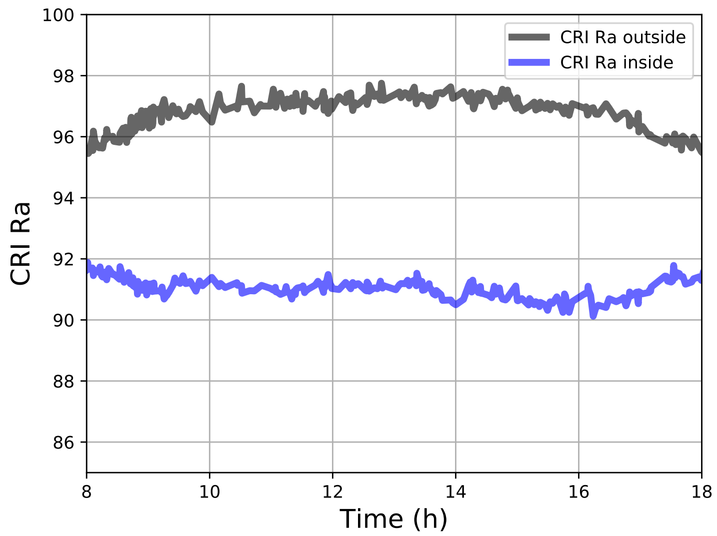

Figure D.6: CRI Ra comparison between measured daylight outside (black lines) and measured light inside at desk level (blue lines).

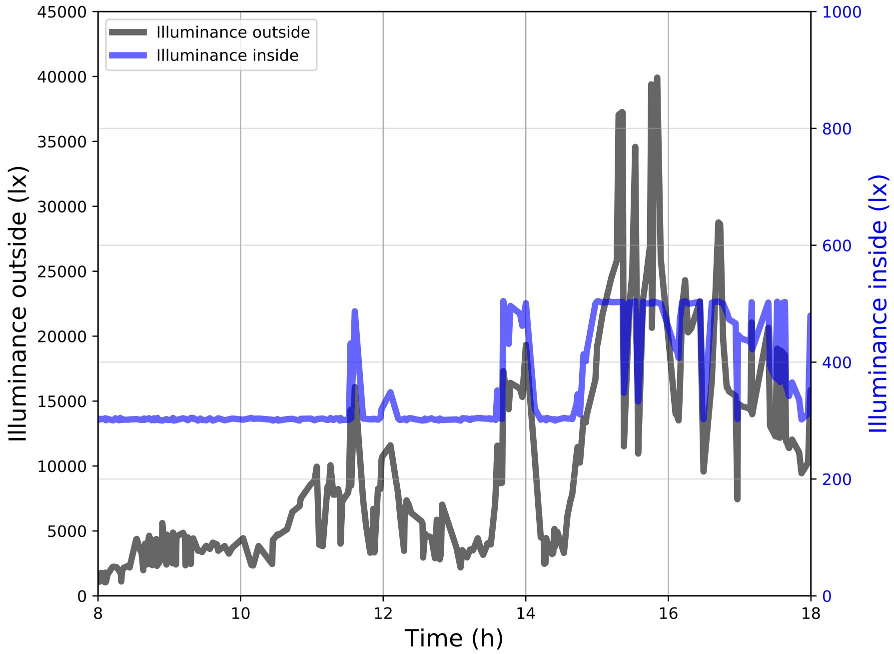

Figure D.7: Illuminance values measured outside (black line, left vertical axis) and illuminance values measured inside at the desk level (blue line, right vertical axis).

With the most nearby windows completely blocked and no access to direct sunlight, working only under fluorescent lamps was a tough experience for most of the participants: "uninspired", "sleepy", "bored", "confined", "tired", "de-energised", "not stimulated enough", "depressed" and "unimportant" were repeated comments during that condition. "The absence of daylight and a view out is very unpleasant; I feel like I am working at night when it is the middle of the morning. It's very unsettling". "I feel like I am working at night all the time. It's affecting my sleep and my mood and it's very uncomfortable".

The experience changed when participants were unknowingly under the real-time daylight matching condition: "busy", "lively", "active", "good", "quite active", "alert and focused", "energized, the colours look good to me", "it is clear and feels purposeful", "interesting, on occasion there are noticeable shifts in colour", "the light makes me feel more lively and connected to the outside, it has a subtle variability", "it feels darker at the day goes on", "the colours look realistic, colour temperature is just right, and so is the intensity", "looking at it as part of the complete open floor lighting scheme doesn't look detached which contributes to make me feel comfortable".

Figure D.8: Picture of the office with the spectrally tunable lighting system installed and the windows blocked.

D.4 Conclusions

Experiences like this project set a new paradigm for indoor lighting never possible before. Using spectrally tunable lighting systems, we were able to copy in real-time the daylight spectra arriving at a spectrometer placed on top of the roof of an office building and transferring the smooth changes in illumination and wavelength components inside as it happens outdoors.

The dynamic system had a relative spectral error equal or lower than 10% when compared to daylight, lower than traditional lighting systems with spectral error values of above 32%. CCT values were mimicked in the office and measured at desk level and had a difference of less than 50 K. The anonymous comments from the participants showed an improvement in their subjective experience when the traditional fluorescent lights were replaced with the system we developed.

As designers and architects increasingly seek to create comfortable spaces and visually stimulant and engaging environments that do not negatively impact people, our methods ensure a natural circadian approach in tune with the human diurnal need for illumination and darkness cycles. In the future, to make it more pleasant, it may be interesting to work on a less glary optical solution (for example, using diffusive panels instead of downlighters), and allow each person to adjust the intensity of their closest light fixture so that everybody can feel more comfortable using its own configuration.

Appendix E

The Intensive Care Unit (ICU) in Hospital Vall d'Hebron

The new smart ICU at Hospital Vall d'Hebron was unveiled in September 2018. It is the biggest ICU in Spain and was equipped with the most advanced systems. All patient information is linked to a smart screen where hospital staff can monitor their progress, a system of blue light codes in front of each patient room warns of their condition i.e. critical or otherwise (see Fig. E.3), and the doors open automatically allowing for easier access. The unit is expected to attend to approximately 2,200 patients each year.

We designed a smart lighting system for the entire ICU, that is, the patient rooms, hallways, and common spaces (see Fig. E.2 and Fig. E.3). Our system was designed to be dynamic (it continuously changes, sending new spectra every few milliseconds), change the photopic lux and melanopic lux (high illuminance values in the morning to wake up and low illuminance values in the evening to favour sleep), and change CCT from cool to warm light (see Fig. E.4). Fig. E.1 shows the design of the light sequence, values of the CCT, photopic lux and melanopic lux at bed level for every 24-hour cycle.

The installation received a lot of attention from media i.e. local and national news agencies, and some articles were published featuring our technology (see E.5).

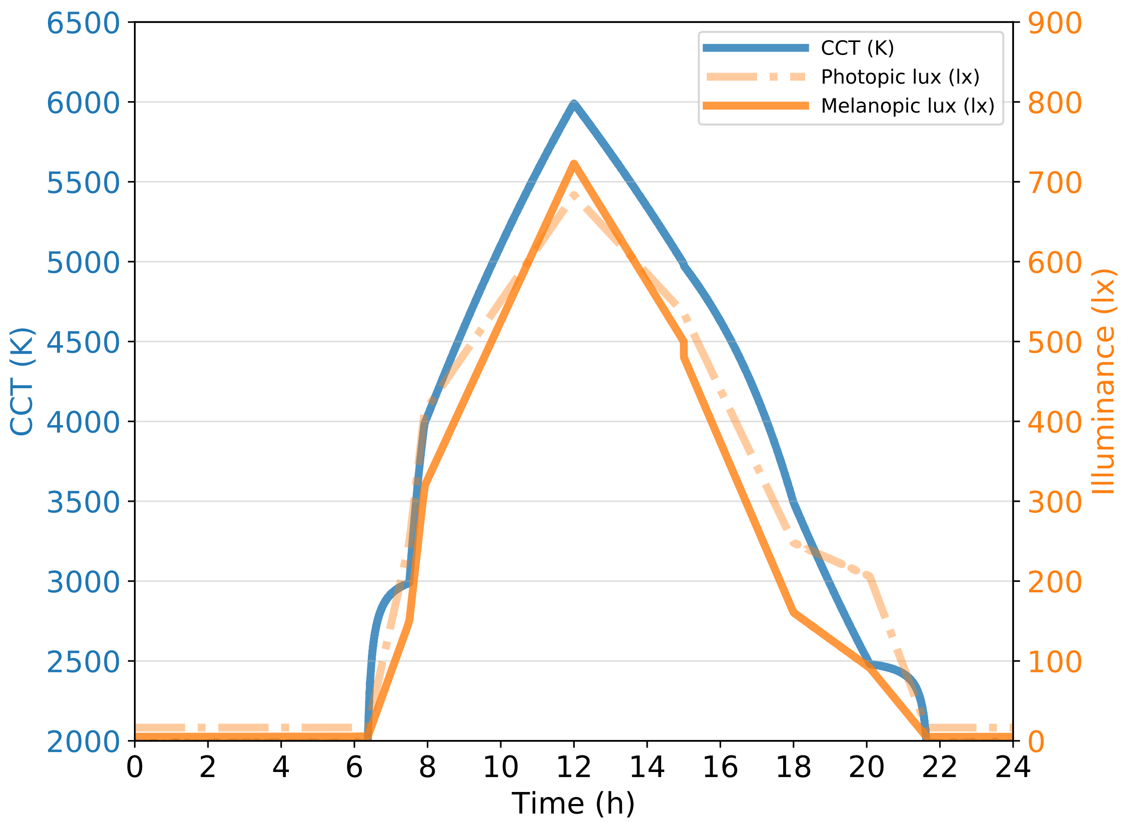

Figure E.1: The sequence in the Hospital Vall d'Hebron was designed to have a changing CCT, changing photopic lux and changing melanopic lux during the day. The colour quality is always CRI Ra > 95.

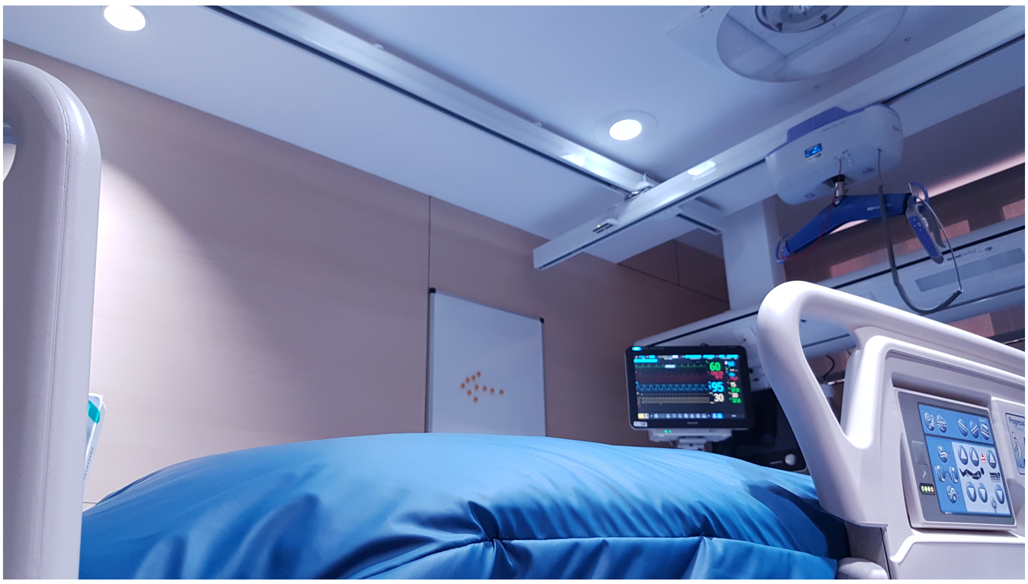

Figure E.2: Picture inside a patients room with the lighting system.

Figure E.3: Picture of the hallway with the blue light code activated, to help the staff identify which patient is needing urgent assistance.

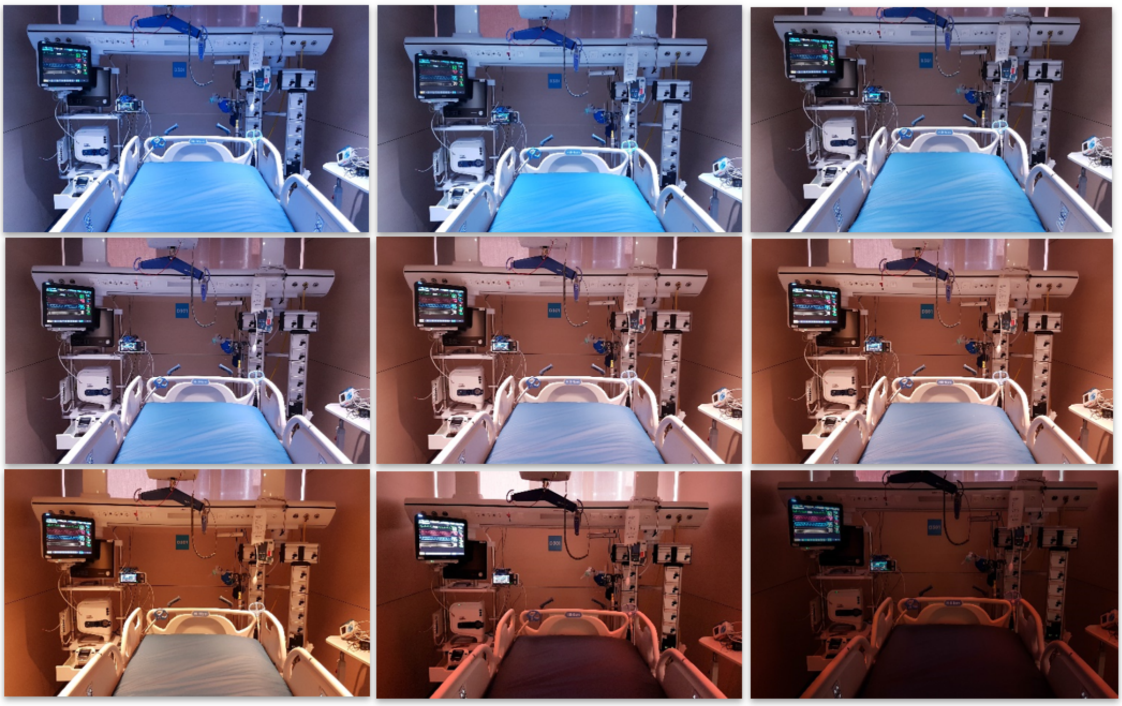

Figure E.4: Pictures of the patient's room at different times of the day, showing the changes in the lighting system.

betevé

a la carta programes programació cinema seccions barris

directes

avui destaquem operació antidroga Ciutat Meridiana - repunt robatoris Sant Antoni - rescat Open Arms - insectes Sant Martí

societat salut

L'Hospital Vall d'Hebron estrena una UCI intel·ligent

El nou sistema permet millorar l'atenció mèdica i fer més agradable l'estada als pacients

Laura Arias | dimecres, 12 de set. del 2018, a les 20.40

L'Hospital Vall d'Hebron ha estrenat una unitat de cures intensives (UCI) amb tot l'**equipament mèdic connectat a un sistema de control central que integra tota la informació sobre cada pacient** i facilita la presa de decisions. Es diu Smart Display i és capaç de mostrar cinc paràmetres bàsics dels pacients en temps real i en una sola pantalla. Aquesta tecnologia pionera **s'ha instal·lat en les 56 habitacions que integren la nova UCI,** 16 més que abans, que passen de ser dobles a individuals. En total, **3.500 metres quadrats repartits en tres mòduls**.

La consellera de Salut, Alba Vergés, ha visitat les instal·lacions durant la inauguració i ha destacat que les eines tecnològiques facilitaran que la feina dels professionals es pugui fer "amb més seguretat i confortabilitat", i també ha apuntat que millorarà l'atenció als pacients "en uns moments crítics per a aquestes persones i també per als seus familiars".

Llum que simula el sol

De fet, les novetats no s'orienten només a millorar l'atenció mèdica. També n'hi ha d'encaminades a fer més agradable l'estada dels pacients. Un sistema d'il·luminació **simula la intensitat de la llum del sol en funció de l'hora** del dia per ajudar els pacients a mantenir els cicles de son i vigília malgrat que estan dins d'una habitació. També és pot graduar la llum de manera manual en 10 posicions diferents, de més a menys claror.

Cada habitació també disposa d'un codi de llums a l'entrada, visible des del passadís. El vermell avisa d'un soroll fort a l'habitació, ja sigui del pacient o d'una visita massa sorollosa, i el blau alerta que alguna cosa no va bé i permet localitzar de seguida l'habitació on cal intervenir amb urgència. Una **gran pantalla situada a cada mòdul ofereix informació de totes les habitacions a temps real**. També els llits donen informació sobre constants vitals o temperatura corporal del pacient. És el primer sistema a Europa que **connecta els llits i aporta informació a un control central**.

Tota la informació que recull el sistema **s'emmagatzema en una gran base de dades que facilitarà, més tard, l'obtenció de patrons històrics**. Segons el gerent de l'Hospital Vall d'Hebron, Vicenç Martínez Ibáñez, aquesta eina "ajudarà a aprendre i millorar les dinàmiques de treball a la unitat" i a perfeccionar els patrons d'actuació. El canvi tecnològic de l'Hospital Vall d'Hebron ha costat **20 milions d'euros** i està previst que atengui uns 2.200 pacients cada any.

el més vist

Nou detinguts en l'operació dels Mossos d'Esquadra a Ciutat Meridiana contra el tràfic de droga

Tanquen tres menjadors socials de Barcelona que donen servei a 300 persones

L'Ajuntament defensa l'eficàcia jurídica del PEUAT, demana aclariments al TSJC i avisa que pot recórrer-hi en contra

Festes Majors de Barcelona 2019: calendari de les festes majors als barris

Veins de Sant Martí de Provençals alerten d'una possible plaga de la

publicitat

Figure E.5: Article in the Barcelona TV news website.

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